Does Integrated-Circuit Fabrication Show the Path for the Future of Mechanical Manufacturing?

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> Everything that can be invented has been invented.
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> Charles H. Duell, Commissioner
> U.S. Office of Patents, 1899

> The solution that is not ready in time is not a solution.
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> Edward Hodnett
> *The Art of Problem Solving* (p. 80)

A Brief History of Component and Assembly Manufacturing

For centuries the majority of manufactured goods have been built by the "shape first, assemble later" paradigm. In other words, individual components are cast, molded, stamped, milled, turned, and so on, then assembled into systems and products. For example, the automotive, aerospace, and—until recently—the Swiss watchmaking industries have adopted the same methodology. Differentiated by the rate of production and by the component size, these industries have achieved remarkable levels of performance and reliability. The automotive and aerospace industries are likely to thrive on this paradigm for a few more decades. The traditional Swiss watchmaking industry, on the other hand, has faded because the demand for packing more and smaller components into the same volume had reached the limits of economically handling small parts with automated devices. While the manufacturing process of traditional watches had reached its limit, more accurate and economical ways of recording time have been invented with the help of advanced electronics. During the last two decades, integrated-circuit (IC) fabrication technology has largely replaced mass production of traditional mechanical watches.

In sharp contrast to conventional manufacturing, the IC fabrication industry has made devices and systems based on a different paradigm. Thin layers of metal and ceramic materials are sequentially deposited and shaped, using techniques such as chemical vapor deposition (CVD) and sputtering, lithography, masking, and etching. Oxidation, doping, and heat treatment may further modify material properties of individual layers. The key difference from traditional mechanical manufacturing is that shaping and assembly occur simultaneously and incrementally.

During the 1980s, the research community started to apply IC fabrication technologies, such as very large-scale integration (VLSI), to domains other than mere logic devices. The feasibility of building small sensory devices, actuators, and motors was demonstrated by a number of microelectromechanical systems (MEMS) researchers. MEMS technology is not associated with one particular process, but rather encompasses a rich variety of process flows. Devices are fabricated by a sequence of conventional VLSI unit processes, including oxidation, diffusion, photolithography, etching, sputtering, and CVD. Augmenting these are new processes developed especially for MEMS, such as wafer bonding and deep reactive-ion etching. The feature size of MEMS devices is one or two orders of magnitude below the size scale where the Swiss watchmaking industry left off, but one or two orders of magnitude bigger than the resolution that is easily achievable in current VLSI fabrication plants. Another important characteristic is that most artifacts built with VLSI fabrication techniques have rather flat geometries. Incremental layer-building inherently facilitates the construction of devices with high eccentricities normal to the building direction.

Independently from but parallel to the developments in MEMS, another research community started to generate three-dimensional (3D) mechanical structures by decomposing computer-aided design (CAD) models into thin cross-sectional slices and then embedding one cross section on top of the other in complementarily shaped sacrificial supports. Various embodiments of this method, called layered manufacturing, or solid freeform fabrication (SFF), are commercially available and well publicized.[1] The majority of SFF processes employ material-deposition strategies ranging from laser-induced curing of monomers, to selective deposition of metal and polymeric powders, to laser fusion of streams of metal powders. Some SFF technologies combine material addition with material-removal strategies such as computer numerical control (CNC) machining.[2] To date, the most important limitations of these technologies are related to material variety and quality, geometric accuracy, surface finish, and rate of production. Major benefits stem from the ease of planning, even for highly complex shapes. Possibly an even more important aspect of incremental fabrication is the opportunity to build custom-tailored material structures with varying chemical compositions suited to local materials-property requirements such as improved thermal conductivity or resistance to abrasion. Structures fabricated in an incremental fashion can be also equipped with local intelligence such as sensors and processors to monitor material-state variables including temperature, stress, and fatigue history. While imaginations may be limitless, material and process constraints pose severe limits on the practicality of such ideas. In the following, we hint at a few design and fabrication methods, some of which are currently being explored at the Rapid Prototyping Laboratory at Stanford University.[3,4] First, we investigate how SFF methods might enhance the functionality of individual components. Then we consider products and the design process.

Materials Challenges For The Next Century presents a series of articles speculating on the role of materials in society in the coming century and beyond.

The Component Perspective: Embedding "Smarts" into Mechanical Parts

Mechanical tools and components are frequently exposed to harsh environments such as corrosion, fatigue, and elevated temperatures. Consequently, these tools are prone to sudden failure, causing costly interruptions of service. Monitoring material integrity during operation may provide early warnings about imminent failure. Examples include turbine blades in jet engines, drill bits in excavating equipment, cutting tools in CNC machines, and pressure vessels and steam pipes in power plants. Two variables provide valuable information: temperature and deformation history. Deformation is measured as accumulated strain, the elongation of a structural component divided by its original dimension.

A variety of physical phenomena can be utilized in order to gather temperature information. One of the most versatile and economical ones is the Seebeck effect, according to which a voltage appears between two ends of a metallic strip when the ends are at different temperatures. Since the magnitude of the voltage depends only on the temperature difference and the material, two strips of dissimilar metals can be joined at one end and an electrical potential difference between the other two ends can be measured when the junction is at a different temperature than the free ends. This construction is called a thermocouple and is widely used in industrial and scientific temperature measurements up to 1400°C.

Strain measurement is conceptually simple, too. Since the resistance of a metallic conductor depends on its geometrical features (length and cross section), any deformation changing these features will lead to a change in resistance. In the case of an elastic deformation (where no permanent deformation is imparted), it is possible to mathematically relate the shape change to the resistance change. By suitably joining a conductor on a structure in a rigid fashion, it is possible to monitor local deformation of the structure by measuring the resistance changes in the conductor.

Thermocouples and strain gauges can be attached to tools, components, and structures in order to monitor their temperature and strain. However, at times, it is necessary to gather information from extended areas, which can only be done by using entire sensor arrays. Installed one by one, the sensors in such an array would be very expensive and time-consuming. Furthermore, the tools or structures could be used under tough environmental conditions, which would render exposed sensors unusable.

To address the needs of sensor-array construction and sensor protection, the specifics of two different fabrication methodologies have been harnessed in the Rapid Prototyping Laboratory.[5] Sensors can be created using thin-film technology very similar to that used for the production of ICs.

The fabrication of objects in a layerwise fashion by SFF methods provides access to their "internal" surfaces. If sensors are deposited onto such a surface of an unfinished object in a thin-film form by techniques that can easily lend themselves to parallel processing (e.g., in IC fabrication, a large number of chips are fabricated in parallel on a single wafer), then they can be embedded ("buried") inside the object when subsequent layers are built to complete the structure. Of course, there should be a way to access the sensor in the completed part, and thus the leads to the sensor need to remain uncovered.

Since sensors represent electric circuits and the structures of interest are frequently metallic, it is necessary to provide insulation for the embedding material. The insulation is deposited on an "internal" surface by vacuum deposition techniques capable of producing compound films. The reason for this is that all insulating materials that can withstand elevated temperatures are ceramic compounds, such as silicon dioxide, aluminum oxide, and silicon nitride. Evaporation, rf, and reactive sputtering are techniques that deposit such films in a "physical" fashion. Insulating ceramic films can also be produced by methods that are described as chemical, such as CVD, where complex gaseous substances are injected into a reactor and, at high temperature or under a plasma, react and form the desired product. It should be noted that the surface onto which thin films are grown must have a low roughness and no contaminants, so that the insulating layer, which is only a few µm thick, can adhere strongly to the substrate.

Similar to insulators, sensor materials are deposited by thin-film techniques such as sputtering, which guarantees that the film will have the same composition as the original alloyed material. Sensor films may be shaped by means of micromachining, which is a technique extensively used in IC fabrication and involves methods such as photolithography and the chemical removal of materials.

Next, the thin-film structure has to be protected, not only from the environment, but also from the deposition of subsequent layers of the embedding structure, especially when these layers are metallic in nature. Since the mechanical properties of metals such as strength and hardness are density-sensitive, it is important that the deposited materials are fully dense. Generally, fully dense metals can only be acquired from a melt, or from a combination of high-temperature and high-pressure processing conditions. This requires protecting the thin films from exposure to the high temperatures that are bound to occur during deposition of the embedding layers. Consequently, a number of protective layers are deemed necessary to reduce the effect of elevated temperatures on the thin films. The latter would be vulnerable either to thermal shock or to large thermal-strain mismatch with the metallic substrate. Thermal shock is a hazard because of the low thermal conductivity of ceramic materials, which can cause localized and inhomogeneous thermal expansion, ultimately leading to delamination. Thermal-strain mismatch is caused by the often-dramatic difference between the coefficients of thermal expansion (CTEs) of the ceramic insulator and the metallic substrate: elevated temperatures may cause the metallic substrate to expand much more than the over-deposited thin film, leading to cracking and/or delamination.

Copper and nickel are examples of materials that can be deposited on top of thin films and provide both a relative homogenization of the temperature field (due to the high thermal diffusivity of copper) and a reduction of its magnitude (due to the lower thermal conductivity of nickel). They can be grown by electroplating, a deposition method that is carried out at room temperature. Its only prerequisite is a conductive substrate. To meet this condition, a "seed" metallic film can be deposited on the ceramic insulation by sputtering or evaporation.

Once the sensory structures are hermetically encapsulated, the incremental component building process can proceed by adopting faster, albeit thermally more aggressive, deposition methods such as laser welding or cladding. Unfortunately, all layered manufacturing processes that employ high-temperature deposition steps suffer from the accumulation of residual thermal-stress fields: Stresses due to different thermal expansion or compression experienced by layers at different temperatures become "frozen" in the structure and may lead to deformation or delamination.

As an alternative to the embedding of thin-film sensors, the incorporation of fiber-optic sensors into materials structures also offers the possibility of measuring varying stress and temperature fields in real time. The embedding sequence, with the exception of the electrical-insulation step, was shown to be practical for encapsulating fiber-optic sensors into steel structures.[6]

The Origin and Possible Reduction of Residual Stress Fields

Thermal stresses develop due to nonuniform shrinkage during material deposition. Nonuniform shrinkage develops for two reasons: temperature gradients generated during material deposition and changes in the CTE in multimaterial structures. These stresses are similar to the thermal stresses that accumulate during IC fabrication when layers of insulators and conductors are deposited onto a wafer. As a consequence, residual stress fields accumulate, which induces wafer curvature and possible layer delamination.

A spectrum of strategies exists to reduce the amount of accumulated residual stress. However, because of the nature of thermal-deposition processing, it is difficult if not impossible to remove thermal stress fields in their entirety. Improved process strategies and improved deposition-material choices can help to reduce the thermal stress and result in lower part distortion.

Several process strategies can reduce the amount of accumulated thermal stress.[7] First, the substrate can be heated before deposition. For example, by preheating the substrate to 400°C, the temperature gradient is reduced to an extent that a 60–70% reduction of residual stresses occurs. Second, the deposit pattern chosen has a significant effect on substrate deformation. By choosing the appropriate deposition pattern, the deflection can be minimized along a critical direction or uniformly lowered in all directions. In addition, depositing thinner layers and firmly bolting the substrate flat during deposition can also reduce overall component deflection.

Thermal stresses can also be reduced through proper material choice. For example, residual stress fields can be reduced by selecting materials with low CTEs. Depositing Invar, an iron-nickel alloy, the deflection can be reduced by 40% as compared with depositing 316 stainless steel.[4] However, Invar has a relatively low tensile strength. This problem can be solved in rapid prototyping processes where the deposited material was originally in powder form. With the help of these techniques new alloys can be produced, in particular by mixing various powder compositions before deposition and fusion. For example, by mixing Invar powder with titanium carbide powder, an alloy that retains a low thermal expansion but has a higher strength than Invar or 316 stainless steel can be produced.[8] A second example of a material that can reduce thermal-stress fields is martensitic steels. These steels undergo a volume expansion during cooling as they transform into martensite. This volume expansion counteracts the contraction associated with cooling. Link et al.[9] showed that by using this material, the deformation could be reduced by as much as 70%, as compared with 316 stainless steel.

The deposition of functionally graded material is a further example of how material choice can reduce cracking induced by residual stress. A functionally graded material is a single, solid piece of material that exhibits spatially varying materials properties. Problems can result in multimaterial parts that have sharp interfaces between dissimilar materials. Discontinuities in the CTE can result in large local stresses and can lead to delamination or cracking. By producing a material with smoothly varying material properties, the cracking and delamination problems can be minimized. It should be remembered that local deposition processes such as laser welding induce high cooling rates due to the small mass of molten material relative to the large mass of solidified material surrounding it. High cooling rates allow "freezing-in" of metastable microstructures, which can potentially increase the design space of possible alloy compositions.

Increasing Component Complexity of Composite Parts

Dramatically improved performance of mechanical properties such as stiffness-to-weight ratio has been achieved through the use of composite materials (e.g., carbon-fiber-reinforced polymers, or CFRPs). However, limited application of composites in the past is to a significant extent related to high tooling cost, slow production rates, and difficulties associated with the assembly of composite components. Traditional fastening technologies, as commonly practiced in the joining of metal parts, are of limited use in composites. Low fracture toughness of composite materials complicates usage of holes, screws, and rivets. In addition, joining of composites with adhesives often requires development of expensive and special-purpose process steps. In the future, SFF methods may allow for direct fabrication of composite parts with complex shapes, thus facilitating the component assembly process or even eliminating certain assembly steps altogether. Early experiments toward freeform fabrication of complex composite parts by laminated object manufacturing (LOM) appear promising, but are far from widespread usage. LOM is a fabrication method belonging to the class of SFF processes.[10]

The Assembly Perspective

The "shape first, assemble later" paradigm of traditional mechanical manufacturing imposes constraints on the geometry of individual components. For example, consider assembling a ship in a bottle. Conventional wisdom would strongly advise against the fabrication of such a configuration, due to expected assembly-interference problems. In layered manufacturing, however, the decomposition of ship and bottle into thin slices, followed by incremental and simultaneous buildup of both, poses no additional planning complexity. Clearly, an appropriate sacrificial support material needs to be placed as a buffer between ship and bottle as they grow simultaneously to their final form.

The benefits of removing traditional geometric constraints are illustrated with a more practical example from the tooling domain. Injection-molded tool cavities and cores frequently have cooling lines embedded to balance the heat flux. An experienced toolmaker attempts to decompose the tool design into subcomponents such that proper facilities for cooling lines are inserted during tool assembly. Lead times of several months are common in the tooling business, due to the high degree of complexity in planning and building. Layered manufacturing potentially offers the opportunity to dramatically cut these lead times. Tooling no longer requires complex decomposition and assembly steps; rather, it can be built as a single entity with significantly less planning effort. Early experiments appear to confirm this hypothesis.[11]

The Designer's Perspective

In traditional mechanical design, a top-down design process is difficult to achieve. Step-by-step translation of functional specifications into physical objects requires years of experience, and success does not come easily. This can be attributed to the lack of a clear-cut functional decomposition of most mechanical components. Also, bringing manufacturing constraints upstream into the early design stages proved to be more difficult than anticipated by the design community a few years ago. Expressing manufacturing knowledge in the form of simple design rules was discovered as a bottleneck in the design process. This in turn results from a lack of proper abstraction schemes in mechanical design, which are significantly more difficult to develop in a 3D mechanical world versus the mostly 2D world of electrical and electronic systems. Emerging feature-based CAD systems for mechanical design will ultimately facilitate a better representation of manufacturing knowledge and constraints. In the meantime, mechanical design will remain highly iterative and subject to frequent trial-and-error procedures.

Top-down design is much more prevalent in electrical and electronic engineering, where functional decomposition of systems is performed routinely. Abstraction schemes are well established to express constraints for a spectrum of IC fabrication processes. These rules are conveniently accessible by designers from within VLSI-CAD frameworks. In fact, current successful VLSI chip fabrication would not be possible without the existence of hundreds of proven design and production-planning tools.

Drawing analogies between the design of mechanical and electronic systems will remain difficult. However, when only considering the production-planning process for VLSI, MEMS fabrication, and layered manufacturing, striking similarities exist. In all cases, the planning process occurs in a largely flat world, which facilitates feature definition and automatic feature recognition from CAD representations. Hence, the complexity of expressing manufacturing rules and presenting them to the designer will sooner or later become similar in both domains. Design/manufacturing protocols for VLSI as currently practiced in most industrialized countries are likely to be established for layered manufacturing with comparable effort.

A bottleneck frequently encountered in traditional manufacturing is "part fixturing." In contrast, parts made by SFF methods are always fully embedded in a support structure, hence planning and manufacturing of complex and expensive fixturing devices is largely eliminated.

Changing Design and Prototyping Environments

In the future, design and manufacturing will be conducted by globally distributed, multicorporate teams that reconfigure rapidly to generate and fabricate new products. Limitations regarding functional decoupling will frequently determine the degree to which design tasks can be geographically distributed.

Once a design is completed, effective communication for prototyping or manufacturing over the Internet will be crucial. "Overnight" prototypes can significantly influence the design direction that a team intends to pursue. Numerous reports on the use of layered-manufacturing technologies over the Internet seem to confirm the potential benefits of rapid experimentation with physical hardware. We anticipate an even larger impact on product development once functional prototypes can be delivered within days rather than the weeks or months that is common in current development environments.

Communicating complete designs electronically has long been practiced in VLSI design and fabrication. In the past, similar attempts in the mechanical domain have failed, since manufacturing difficulties related to part-specific tooling and fixturing could not be anticipated. Realistic 3D simulations will significantly help to envision downstream problems. However, decomposing parts into thin subsections and eliminating fixturing requirements altogether due to the embedding of parts into sacrificial support structures are also considered crucial steps toward decoupling design specifications from fabrication processes. Incremental fabrication of material structures, layer by layer, or almost pixel by pixel, will further increase the spectrum of development and production tools available at the fingertips of next-generation designers.

Manufacturing in an incremental fashion—be it layer by layer, pixel by pixel, or ultimately, molecule by molecule—will have some far-reaching consequences, since it will lead to materials with previously unheard-of properties. As an example, consider materials with a negative CTE or Poisson ratio, or materials with spatially varying physical properties. Advanced capabilities in materials synthesis would inadvertently lead to the creation of novel products. One can envision components with a significantly improved lifetime due to built-in compressive stresses in the vicinity of the surface, or parts that keep track of their fatigue history, telling their users the best time to replace them. Conflicting functional requirements could be resolved by assigning different properties to different portions of a structure. Computational optimization could be used to synthesize the best shape with the best spatially varying material composition. The imagination of the potential benefits and opportunities of "designer materials" is unlimited, yet their realization will not come without significant insights into the underlying theory and practice of materials science and manufacturing.

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