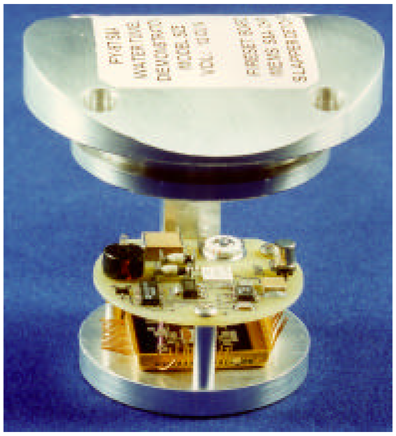
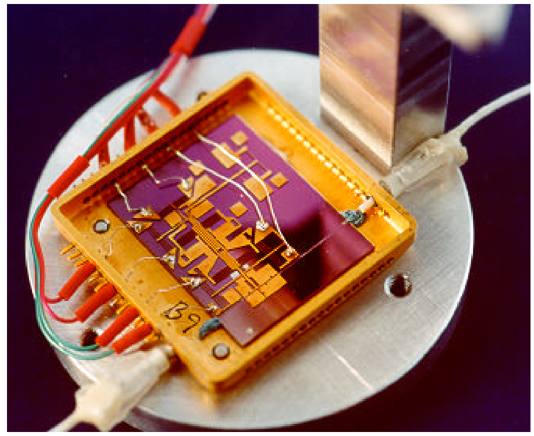
Integrated Nano-to-Millimeter (In2m) Systems



Torpedo Safety & Arming/Fuzing Prototype System



MEMS Safety & Arming Chip

Open Forum Editorial:

Systems that Span Nano-to-Millimeter Size Scales

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Article:

Nano-to-Millimeter Scale Integrated Systems

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Editorial

Systems that Span Nano-to-Millimeter Size Scales

A great deal of emphasis has been placed on integrating diverse functionality into a single monolithic device for the sake of smallness and performance – but what happens when a system with diverse functionality, materials and technology can not be fabricated monolithically? The integration of systems created from dissimilar elements, especially those that vary in size by orders of magnitude is poorly understood.

This open forum article discusses a class of systems called “Integrated nano to millimeter” (In2m) systems, defined by their multiple size, diverse technology domains, and mixtures of electrical, mechanical, thermal, chemical, fluidic, and biological functions. The modeling, analysis and synthesis of these systems suggests analysis techniques, materials, manufacture and assembly transcending the capabilities developed within individual disciplines. The function and fabrication of a Safety & Arming device is presented to illustrate the In2m concept.

Your feedback on this article is most welcome.

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Nano-to-Millimeter Scale Integrated Systems

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I. Introduction – Small devices with large diversity

With the advent of the semiconductor electronics came the ability to fabricate extremely small devices. In order to use the small devices in real applications, they needed to be interfaced to the macro world through the development of packaging and interconnections technologies. The most common interface technology for this interconnection is the single chip package.

The single chip package can be classified as a one-size, one-technology domain structure, whose evolution has been a trial and error process. The military semiconductor packages of the 1950s to the 1980s were designed and fabricated as one would build a house; although this house was made of metal and hermetically sealed. Commercial designs, which enabled ease of manufacture and assembly, but required additional care in the materials and the manufacturing processes, came into mass production in the 1970s. These new designs enabled mass production using automated assembly line techniques and plastic materials. Eventually it was realized that high quality could also be obtained from this approach, and by the 1990s the military started actively using commercial single chip semiconductor packages. Today, the single chip package has further evolved to chip-scale packages and even now "bare" die with underfill, thanks to multi-chip module development.

The multi-chip module (MCM) can be classified as a one-size, multi-electronic technology domain structure. Although the MCM had its roots in hybrid circuit technologies, it wasn't until the mid-1980s that the push to develop MCMs was initiated. DARPA spent hundreds of millions of dollars on the MCM technologies, only to learn that there was a showstopper, called known-good-die (KGD). The root of the problem was associated with who had the responsibility to ensure that the die comprising the MCM were indeed functional. While a die in a single chip package can be tested after packaging, there was no infrastructure in place to test "bare" die. Similar problems arose due to layout, thermal budgeting, rework and substrate fabrication, but DARPA quickly responded and set up programs to address these issues. Today, some of the solutions that have met commercial success include few chip modules, memory stacks, z-axis conductive adhesives and microvia substrates.

Today's complex hybrid systems move beyond the MCM to include the integration of even more diverse functionality into a single system. Consider the following systems that have size constraints, yet cannot be fabricated monolithically:

> *Safety and Arming (S&A) Device* - The primary functions of a S&A device are to keep the weapon safe, to arm the weapon, and to contain the energetic material necessary for initiating the weapon. At the heart of the S&A device is a microelectromechanical slider that changes positions to either expose or block an explosive train that initiates the weapon (see cover of this issue). The S&A device contains several independent locking mechanisms that block the ability of the slider to move until the weapon has been exposed to a logical sequence of post launch environments. For example, in a S&A device used in a torpedo, a hydrostat senses pressure and only unlocks the slider if the device senses it is at an appropriate depth. The S&A device also includes independent optical verification of its position. Section III of this paper discusses the S&A device in detail.

A Computer Writing Tool – A "smart" pen that allows simultaneous writing on paper and on a computer is under development [1]. The pen uses a standard ink cartridge mounted in a shaft that is connected to a force sensor (Fig. 1) and is monitored by a tilt sensor. A rechargeable battery pack is included to power the device, and at the top of the pen is a printed wiring board containing multiple chips comprising a radio transmitter that communicates with a computer. The position of the pen on the writing surface is computed from information obtained from the force and tilt sensors, and serve as input for displaying a bitmap of the written text on a computer display.

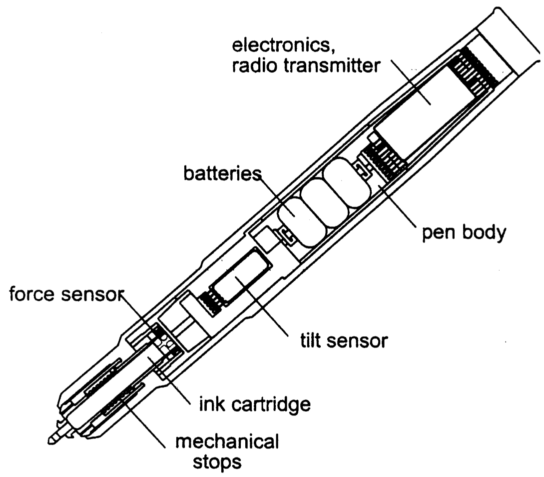

Fig. 1. SmartPen system [1] (Courtesy of IEEE).

Solid Drug Delivery Device – Solid drugs are normally delivered by implanting a highly concentrated dose of a drug subcutaneously so that it is slowly dissolved by the body thereby releasing small amounts of the drug. Unfortunately, not all patients dissolve the drug at the same rate, and the traditional method requires permanent exposure to the drug. If a reliable delivery device that opened and closed in response to external stimuli (either from sensor input or on the patient's command) could be created, many of the problems associated with solid drug delivery would be solved (see Fig. 2 for an example). Such a device requires sensors, actuators, electronic logic, a power source, and must be compatible with the drug it contains.

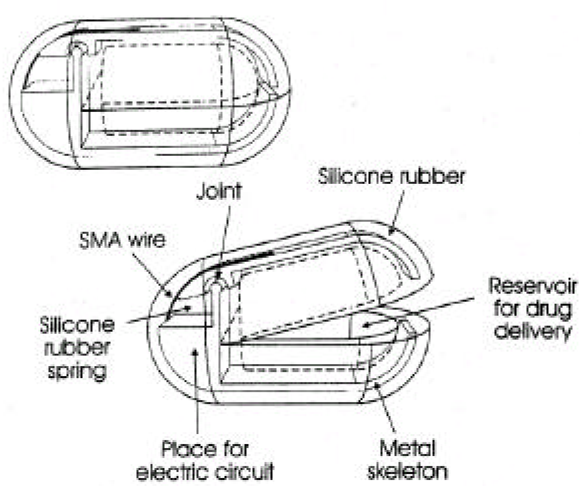

Fig. 2. Solid drug delivery device [1] (Courtesy of IEEE).

II. What is In2m?

Over the last several years various industries have been developing nano, micro, and millimeter scale technologies, which have resulted in components ranging from quantum transistors, to widely commercialized integrated circuits, to microelectromechanical sensors. A common emphasis of these fabrication industries has been on the integration of different functions in miniaturized systems [2]; however, the technology currently used to realize these systems is monolithic.

Some systems require a diversity of functionality that cannot be fabricated monolithically. Construction of these more complex systems requires a hybrid of technologies. While considerable advancement has been made in creating homogeneous systems, integrating dissimilar technologies into small, manufacturable products is much less mature. The examples given in the previous section have the following common threads:

- They cannot be fabricated monolithically because they span many processes and materials;
- Their application requires real-time interaction with their local environment such as temperature, acceleration, orientation, and pressure;
- They span many orders of physical size, from submicron integrated circuit structures to millimeter scale actuators and sensors;
- They convert energy from one size scale to another;
- They involve multiple disciplines: electrical, optical, mechanical, chemical, and fluid [3].

The unique class of systems defined by all of these requirements are referred to as *Integrated nano to millimeter (In2m)* systems [4]. An In2m system typically has components spanning multiple sizes, diverse technology domains, and mixtures of electrical, mechanical, thermal, chemical, fluidic, and biological functions.

III. Understanding the In2m concept: A case study

We have chosen for our case study the development of a Safety & Arming (S&A)/Fuzing device that can be used in undersea weaponry, an effort being led by the Naval Surface Warfare Center, Indian Head Division [5]. An ONR/DARPA funded technology program commenced in 1994 as an investigation into adapting microelectromechanical technology for use in the development of next generation undersea weapon systems and into evaluating the potential of applying such a system across the entire spectrum of Navy weapon systems. The primary function of a S&A device is to provide for weapon system safety; i.e., protection of personnel, equipment, and vessels against premature warhead detonation. This protection is provided through what is called the "stockpile-to-target sequence", which spans the period through moving the weapon from its storage location until the time of weapon use against a target. The fuze portion of the system is designed to sense the target and initiate detonation of the warhead. There are several aspects of the S&A/Fuze development process that clearly highlight the challenges of the In2m process.

A. System Requirements

The requirements for the S&A/Fuze system are to reliably arm and detonate the warhead, but only after all safety criteria are met and the weapon has reached the intended target. The functions of the S&A are to keep the weapon safe, to arm the weapon, and to contain the energetic material necessary for initiating the warhead. The S&A independently makes the safety decision for a weapon by recognizing launch environments and maintaining safety during the stockpile-to-target sequence. The function of the fuze is to detect the target and provide the signal to initiate warhead detonation. The design of all S&A/fuze systems is guided by very rigorous military requirements specifications, and must meet extreme environments that constantly push the envelope of the physical limits of materials.

At the S&A/fuze level, the functions of the weapon's S&A system, shown in Fig. 3, are the following: 1) interrupt and lock explosive train (the firing energy path in Fig. 3; 2) sense a minimum of two unique post-launch environmental conditions and events; 3) fully unlock the explosive train only after a safe distance has been achieved from the launch platform; 4) move the explosive train in-line upon receiving a weapon "arm" command; and 5) initiate the warhead by contact/proximity fuze or upon a weapon "fire" command.

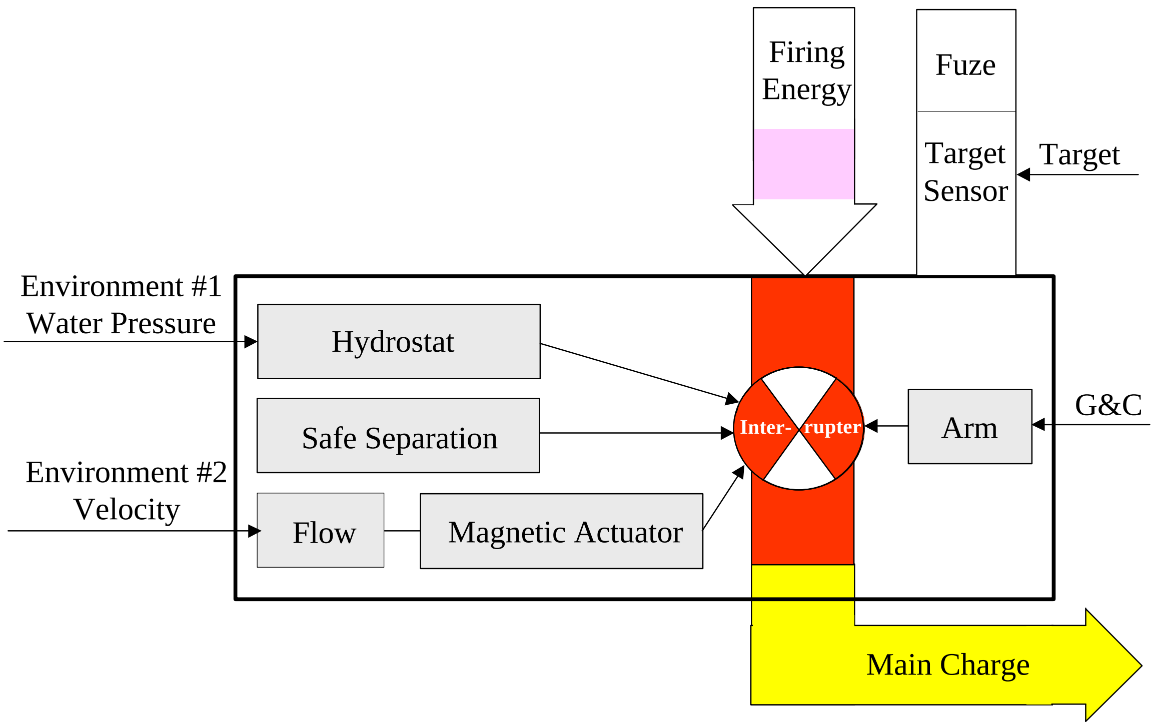

Fig. 3. S&A functional diagram.

In conventional weapons the S&A physically interrupts the explosive train between sensitive initiation elements and booster materials. Military specifications require that S&A's contain two independent safety elements, both of which prevent unintentional arming. Furthermore, it is required that the safety features can only be enabled by stimuli from two independent environments.

Other requirements are weapon-specific, such as a very challenging overall size limit that will result in a hockey-puck sized device, and a cost goal for final engineering development and manufacture of the device. In fact, for many of the weapon systems "on the drawing board" cost is being given equal or greater weight to system performance as a tradeoff variable, but not at the cost of safety.

B. System Description

The S&A chip shown in Fig. 4 provides the explosive barrier, houses environmental sensors, and allows optical indication of device status. The silicon S&A chip is fabricated at MCNC/Cronus combining LIGA and surface and bulk micromachining. The current S&A chip design requires no assembly. Parts are selectively released to achieve the desired combination of moving and fixed structures. As each environment is sensed, a lock is removed from the barrier (the slider). Once all the locks have been removed and the fuze decides it is time to arm, the barrier (slider) is moved out of line so that the explosive train may detonate.

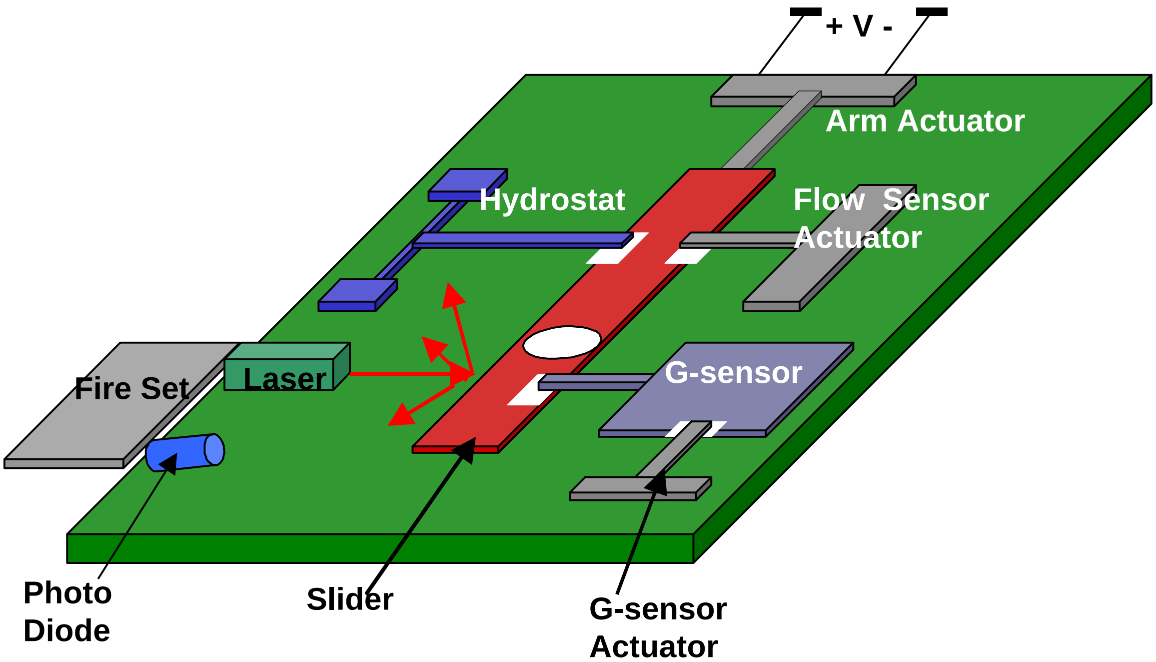

Fig. 4. Key components of the S&A fuze systems.

The key components of the S&A chip shown in Fig. 4 are the following:

- Hydrostat – consists of a bulk micromachined diaphragm, which actuates a LIGA lock on the slider interrupter via a direct mechanical coupling [5];
- G-sensor - mechanically coupled to the slider interrupter to serve as a lock;
- Flow sensor - a micromachined differential pressure sensor to measure flow over the weapon and control a microelectromechanical thermal actuator that serves as one of the physical locks on the slider interrupter; and
- Arming actuator – micromachined thermal actuator used to drive the slider interrupter.

A view of the chip- and carrier-level package is shown in Fig. 5. The chip-level package includes the S&A, initiator chip, and delimiter. The initiator chip converts electrical energy to mechanical energy upon demand to fire the explosive train. The initiator chip is powered by a stripline to minimize inductance. The initiator chip is fabricated at MCNC/Cronus using MEMS technology. The S&A chip and the initiator chip must be reliably bonded together while maintaining precise in-plane and out-of-plane alignment. A coefficient of thermal expansion mismatch between the S&A chip and the initiator chip increases the challenge of maintaining alignment and bond integrity.

A deflection delimiter is introduced to limit out-of-plane (z-axis) compliance of several structures. The delimiter ensures that the locks on the barrier are not violated by z-axis displacement between structures. The deflection delimiter must allow for in plane movement of all structures, but prevent z-axis movement of selected structures. In addition, the delimiter must allow for wire bonding and fiber optic cable routing and mounting.

Carrier-level packaging consists of integration of the chip-level packaging with the carrier. The carrier provides the transition from the micro-scale to the macro-scale. In the present system, the chip-level assembly interfaces with the macro environment through the following links:

- traditional electrical interconnects
- stripline
- pressure
- fiber optic
- explosive.

Military guidelines also call for a visual indication of the S&A status; i.e., personnel must be able to see if the weapon is in a safe or arm mode. The S&A device is safe if the slider interrupts the explosive train. The fiber optic cable as shown in Fig. 5 is routed through the carrier and onto the S&A chip. Light reflects off the barrier (slider) and into one of two fibers, indicating the safe or arm condition.

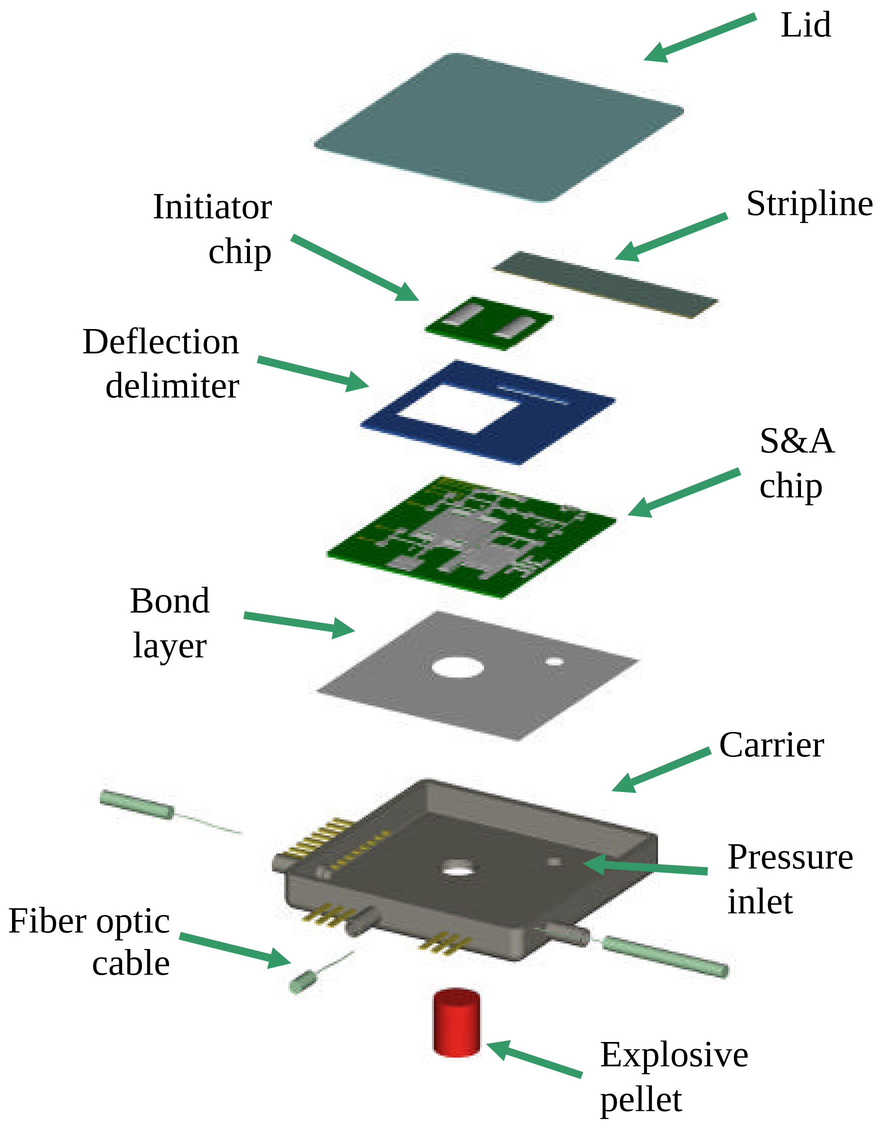

Fig. 5 Carrier-level package.

IV. Challenges in the Evolution of In2m Systems

Emerging technologies that produce new devices are primarily at the proof-of-concept level. When new devices are required to satisfy the requirements for their economical manufacture with predictable performance characteristics, difficulties often arise, some severe enough to prevent their further development and subsequent appearance in the marketplace. This development process is further complicated when attempts are made to integrate various devices made by different processes into complex systems, as is the case with In2m.

The main challenges facing In2m is the integration of the following interrelated areas:

- Packaging and component design
- Assembly
- Reliability assessment and qualification
- Modeling, simulation and system design
- Risk identification and mitigation.

These challenges require research and development in interface methods for several I/O modalities, methods and tools for In2m system design and optimization, methods and tools for determining reliability, equipment and processes, and finally component design for packagability.

A. *Packaging and Component Design*

One of the challenges in package design is hermetic equivalent reliability. In the case study presented in Section III, we saw that this In2m system had moving parts and feed-throughs requiring energy transfer from the micro- to the macro-scales. These features of In2m will be the main challenge to maintaining hermetic equivalent reliability.

For In2m systems to successfully transition to the commercial marketplace, cost effective, reliable packaging approaches need to be developed. For In2m systems, packaging approaches may need to accommodate multiple interfaces, moving parts, hermiticity, and environmental inferfacing.

The moving microsystem structures create difficulty in applying traditional plastic encapsulation techniques. In an effort to use plastic encapsulation, researchers bond a protective cap over the moving structures and then dispense around the seams. The assembly is then ready for plastic encapsulation. But the plastic encapsulation issues don't end there. With the addition of non-traditional vias into and out of the package, several new interfaces are added that are potential moisture ingress paths. The selection of the plastic encapsulation material is much more complicated than for IC packaging. The viscosity must be such that the material will flow around some structures (e.g., wire bonds, fiber optic cables), but not flow into undesirable areas (e.g., moving structures). In addition, the CTE of the encapsulate must be a balance between the several materials it contacts.

When environmental interfacing is needed, designers must take into account erosion and corrosion of parts at micro-scales. These failure mechanisms will need to be understood and characterized for a wide range of new materials being deployed in these new microsystems.

In the development of In2m systems, there will be a need to incorporate many features during component design to ease assembly and packaging, including: alignment structures, assembly aids fabricated with the component, built in test schemes, and in situ sensors to monitor local environment conditions during assembly and packaging (temperature or mechanical stresses). Components designed for specific packaging environments enable In2m systems to operate and be manufactured more cost effectively.

B. Assembly

Integration across multiple length-scales and fabrication technologies will make assembly a critical step in the fabrication of microsystems, presenting challenges in the handling and assembly of the components to be assembled. Typically some components will have parts that move and that may be damaged using current equipment and processes. The assembly may require tight control over both in plane and vertical alignment (< 10 microns in-plane [6]). In some instances components may have thin diaphragms or holes for optical interface or feed-throughs; consequently these chips will not be able to be handled using vacuum transfer equipment. Also equipment that can pick and accurately place micro-scale structures will open require more complex microsystem designs. Recall from our case study that the S&A chip was designed with the constraint that the chip was to be free from microstructure assembly.

C. Reliability and Qualification

The In2m reliability assessment approach must be developed from a Physics of Failure (PoF) [7] methodology, because failure mechanisms specific to In2m systems are not yet characterized. The need for understanding the physical phenomena and failure of components in In2m is complicated by several factors, including the multiple materials and interfaces in the system and the interaction of the system with the local environment.

Qualification is defined as a process to verify whether or not the anticipated reliability is achieved under actual life cycle loads for a specified length of time. The purpose of qualification is to audit the ability of the design, manufacture, and assembly to meet reliability goals. Traditional qualification consists of following decades old "one size fits all" standard tests that are often inaccurate, improperly applied, and unnecessarily restrictive. Development of virtual qualification [8] methodologies will be necessary for the timely and cost-effective fielding of In2m systems.

D. Modeling, Simulation and System Design

There are several aspects of microsystems technology that differ significantly from integrated circuit (IC) technology. Integrated circuits are composed of a limited number of elementary device structures, fabricated by means of well-established and quasi-standardized design rules and process technologies. In the field of microsystems technology, however, an ever-growing variety of different device types are emerging, based on unconventional design methods and widely differing fabrication technologies. Therefore, today's challenge in the design of microsystems is to focus on describing systems with complex topology built up by a comparably small number of constituent devices, each of which exhibit a highly functional complexity based on sophisticated and involved physical operating principles [9].

Microsystems of the future will be inherently highly multi-disciplinary in nature and unprecedented in functional complexity. Commercial success of these systems will depend on being able to transform a market need to a reliable commercial product within few months. Without availability of computer-based design tools, creating a successful microsystem could take years. In order to lay the foundations for creating design tools for microsystems, current design methodologies of VLSI design and mechanical system design will need to be significantly enhanced. The complexity of the next generation microsystems will far exceed that of their VLSI counterparts in terms of component types, functions, geometric shapes, underlying physical laws and spatial integration.

In In2m systems the constituent components incorporate mechanical, fluid, thermal, electrical, and other physical or chemical quantities. As a consequence, the models underlying the simulation tools must be capable of accounting for a large variety of physical coupling effects on both the device and the system level.

The evident prerequisite for the technical realization of this idea is the availability of a set of efficient simulation tools, which fit in with today's far advanced design environments used in the semiconductor industry and, in particular, conform with the widely accepted bottom-up and top-down modeling hierarchies. In this way, just as computer technology radically changed the economics of integrated circuit design over the last decade, computer-aided design is likely to change the economics of microsystems design and manufacture.

The complexity of microsystems originates from a complicated coupling between different energy and signal domains. On one hand, this is the inherent and much desired property of any sensor or actuator element in a microsystem. On the other hand, this is a detrimental property when it occurs as parasitic cross-coupling between the system components is in fact a requirement of the system. Therefore the computational effort as well as the time spent into model development, validation, calibration, and parameter extraction have to be carefully adjusted to the actual needs, as it has been proposed by the concept of "tailored modeling" [9] [10].

E. Risk Identification and Mitigation

The first generation of In2m systems will be highly complex systems incorporating the latest fabrication technologies, but with limited field data. Therefore, successful deployment of In2m systems will require a systematic methodology to mitigate the risks associated with the manufacture, field use, and sustainment of In2m systems. Risks include availability and obsolescence of components, materials and technologies, manufacturing costs and yields, test and rework costs, consequences of field failure, and maintenance costs [11]. In2m design approaches must be "risk informed", otherwise the costs associated with sustaining products that depend on In2m systems will be prohibitive.

Another aspect of risk mitigation is health monitoring. Health monitoring, based on advanced in-situ sensor technologies coupled with Physics of Failure assessment, which compares the condition of the system against the probability of failure occurrence, provide an early warning for a maintenance action. This leads to reduced and more focused maintenance actions, lowered in-service failures, and higher availability [12].

V. A View from the Frontier

In2m systems present a new and unique set of challenges that differ fundamentally from the challenges facing monolithic systems. The difficulties that will have to be overcome in this evolving area will require strong justification as to why one wants to make a "small" device or product. “Smallness” will not be the metric by which In2m system advancement is measured, but rather the diversity of functionality that can be successfully integrated into a practical, manufacturable product.

Understanding the interfaces across which energy and information must flow is key to successful In2m realization. With such an understanding, a world of new applications opens.

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