Packaging for Microelectromechanical and Nanoelectromechanical Systems

Y. C. Lee, *Member, IEEE*, Babak Amir Parviz, *Member, IEEE*, J. Albert Chiou, and Shaochen Chen

***Abstract*—Packaging is a core technology for the advancement of microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS). We discuss MEMS packaging challenges in the context of functional interfaces, reliability, modeling and integration. These challenges are application-dependent; therefore, two case studies on accelerometers and BioMEMS are presented for an in-depth illustration. Presently, most NEMS are in the exploratory stage and hence a unique path to identify the relevant packaging issues for these devices has not been determined. We do, however, expect the self-assembly of nano-devices to play a key role in NEMS packaging. We demonstrate this point in two case studies, one on a silicon nanowire biosensor, and the other on self-assembly in molecular biology. MEMS/NEMS have the potential to have a tremendous impact on various sectors such as automotive, aerospace, heavy duty applications, and health care. Packaging engineers have an opportunity to make this impact a reality by developing low-cost, high-performance and high-reliability packaging solutions.**

***Index Terms*—Accelerometer, bioMEMS, MEMS, NEMS, packaging, self-assembly, sensors.**

I. INTRODUCTION

MICROELECTROMECHANICAL SYSTEMS (MEMS) technology enables us to create different sensing and actuating devices integrated with other microelectronic, optoelectronic, microwave, thermal and mechanical devices for advanced microsystems. Semiconductor fabrication processes allow for cost effective production of these micro-sensing or actuation devices in the 1–100 $\mu\mathrm{m}$ size scale. With feature sizes reduced to 1 to 100 nm, nanoelectromechanical systems (NEMS) technology enables us to explore sensors and actuators with very-precise detection and manipulation of objects down to the molecular levels. MEMS/NEMS provide new technologies with the societal impact that could rival that of integrated circuits (ICs).

Fig. 1 illustrates a typical design and manufacturing process for a MEMS device. This illustration highlights some of the differences between MEMS and microelectronics fabrication and packaging. During the design, solid modeling is required since electro-thermal-mechanical coupling is essential to the functions of most of MEMS devices. The fabrication often involves deposition and etching of miron-thick layers with controlled mechanical and electrical properties [1], [2]. In many devices, after the completion of the fabrication process, the sacrificial materials are removed by etching in order to release the device for mechanical movements. This release process is usually the first step in the MEMS packaging. The released device shown in the figure represents a configuration for pressure sensors or accelerometers or an element of an array for optical micro-mirrors and RF switches. After release, the devices can be tested on the wafer-level, followed by dicing. The released, diced device is assembled and sealed in a package. These testing, dicing, assembly and sealing steps are very challenging. Without proper protection, the micro-scale, movable features could be damaged easily during these steps [3]. As a result, it is always desirable to replace the process illustrated here by wafer-level packaging [4].

Hundreds of MEMS-based sensors and actuators and systems have been demonstrated and the number of their applications is growing. Few examples of their diverse applications are listed as follows [5].

1) Pressure sensors: for sensing manifold air pressure and fuel pressure to decrease emission and fuel consumption; for measuring blood pressure.
2) Inertial sensors: accelerometers for measuring acceleration for launching air bags; gyros for measuring angular velocity to stabilize ride and to detect rollover.
3) Chemical micro sensors: for fast, disposable blood chemistry analysis; gas sensors.
4) Optical MEMS: micromirrors for projection displays; optical switches for wavelength division multiplex switches; attenuators or micro-devices for active alignments for optical microsystems; micro-displays or paper-thin, direct-view displays.
5) Radio frequency (RF) MEMS: micro-resonators for integrated RF transceiver chips; RF switches for millimeter-wave systems.
6) Microfluidics MEMS: DNA hybridization arrays or similar lab-on-a-chips for biomedical and biochemical development, bio-analysis and diagnostic; printerheads for ink jet printing.
7) Power MEMS: on-chip power generation and energy storage for portable systems.
8) MEMS-based data storage: micro-positioning and tracking devices for magnetic, optical, thermal, or atomic force data tracks; micro-mirrors for optical beam steering.

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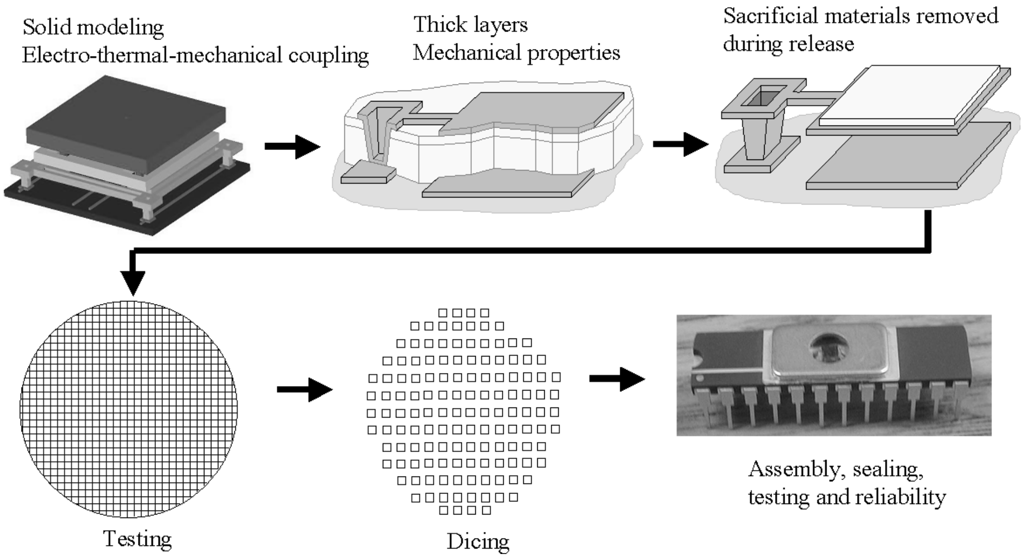

Fig. 1. MEMS design, fabrication and packaging.

9) Microsurgical instruments: for noninvasive techniques, intra-vascular devices and laprascopic procedures.

MEMS provides micro-scale components for a number of applications. Fig. 2 illustrates an interesting example using a micro-resonator [6]. The resonance frequency of this micro-scale beam with two ends clamped, could reach 8.71 MHz with an extremely high quality-factor. As a result, such a micro-resonator can replace a large number of RF components for high-frequency (HF) filters. Such a replacement will significantly reduce the size, power dissipation and cost for future compact wireless communication systems. The resonance frequency of a doubly-clamped beam is given by

$$\mathrm{f}_0 = \frac{(4.730)^2}{2\pi}\frac{1}{\mathrm{L}^2}\sqrt{\frac{\mathrm{EI}}{\rho \mathrm{A}}} \tag{1}$$

where L is the length of the beam, ρ is the density, E is Young's modulus, A is the cross-sectional area, and I is the moment of inertia [7]. By reducing the beam length to $\sim 2\ \mu\mathrm{m}$, the resonance frequency can reach ~400 MHz. By reducing the length of the beam by another order of magnitude to ~200 nm, we could arrive at a nano-scale device with its resonance frequency at ~4 GHz. As indicated by these results, NEMS technology could improve micro-resonator applications for GHz RF filters. These estimates illustrate the relationship between MEMS and NEMS applications. Most of MEMS applications listed above are emerging and will stimulate more novel designs for future engineering and medical systems. Most of NEMS applications are exploratory at the present time. They have the potential to significantly expand MEMS applications in the future.

NEMS-enabled mechanical systems can be used to detect small forces, and similarly, they can be actuated by small forces. In addition to the wireless communication, as mentioned above, NEMS technology may have an impact on ultrahigh-density data storage, molecular resolution magnetic resonance imaging systems, detectors for atto-grams mass change, nanofluidic to sort DNA molecules or for single-molecule detection, and many other exciting applications beyond our imagination today [7].

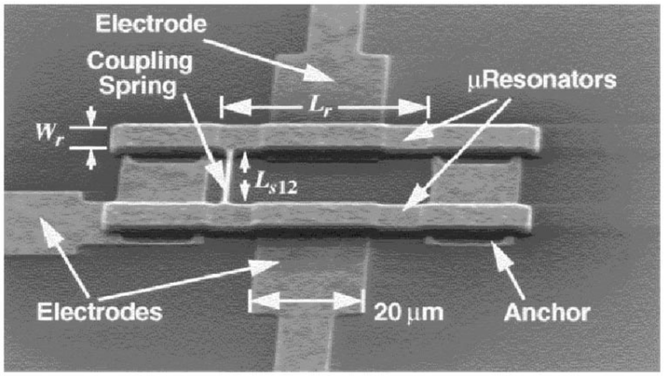

Fig. 2. Micro-resonator for RF applications.

Packaging is a critical aspect of realizing most of these MEMS and NEMS applications. The resonator shown in Fig. 2 would dissipate most of its energy into air and have a small quality factor unless the device is packaged in an ultrahigh vacuum environment. Such a packaging requirement increases the cost substantially and severely limits the integration of the device with other components. Some of the MEMS packaging challenges have been identified and proper solutions have been developed. In the following sections, we will discuss some of them. However, it should be noted that MEMS/NEMS packaging challenges are not fully understood and are usually application-dependent. It is impossible to define common challenges applied to all of the MEMS-based and NEMS-based systems. Most discussions should be treated as examples to help us understand and appreciate these emerging fields.

II. MEMS PACKAGING

MEMS packaging can be defined as all the integrations after the microfabrication of the device is complete. They include post-processing release, package/substrate fabrication, assembly, testing, and reliability assurance. It is sometimes difficult to distinguish MEMS fabrication from packaging. For example, in wafer-level packaging, device fabrication and packaging processes are fully integrated. Reliability is one of the performance measures that are strongly affected by the package as well as the device. Assurance of the reliability is considered as a packaging activity since packaging engineers rather than fabrication engineers usually conduct environmental protection processes, burn-ins, and accelerated tests to ensure the production of a reliable MEMS device.

Fig. 3 shows a package developed for Texas Instruments' digital mirror device (DMD). DMD has millions of micro-mirrors and is used for projection displays. This device has proven an important fact: mechanical devices can be switched over trillions of cycles while achieving the same reliability level as their electronic counterparts [8], [9]. After release, a self-assembled monolayer (SAM) can be used to coat the device to avoid a moisture-induced stiction problem. If needed, getters can be used to remove particles or moisture inside the package [10]. The DMD package is hermetically sealed with a Kovar ring. Particles can cause reliability failures, so the device has to be packaged in a Class-10 cleanroom. Outgasing of all the package materials should also be controlled. The large glass window is the critical optical interface between the DMD and other optical components for a projection system. Therefore, the window's alignment with the DMD is important [10]. Another concern is the hysteresis behavior of the mirror's aluminum material. The mirror may be difficult to move when it stays at one titling angle for too long. This creep-related problem is temperature dependent; as a result, thermal management has to control the device temperature to avoid the hysteresis effect [9].

MEMS packaging has been and continues to be a major challenge. The packaging cost is about 50% to 90% of the total cost of a MEMS product. Although the electronics manufacturing industry has a robust and viable infrastructure, direct application of electronics packaging techniques to most MEMS parts is not feasible due to the complexities of their operational structure and domain. For example, packaging should allow some moving parts to interact with other components through optical, electrical, thermal, mechanical or chemical interfaces. As a result, many MEMS packaging problems are new to most of the electronic packaging engineers. Here are a few examples.

- Vacuum packaging may be needed when viscous damping is important.
- Die-attachment may create severe thermal stresses that affect the accuracy of pressure measurement.
- Thermal strains may affect the performance of membrane devices.
- Moisture can cause stiction problems.
- There are no effective thermal paths for thin micro-mirrors for heat transfer.

There are very few accelerated tests since most of the failure mechanisms of the moving parts are unknown. In a national science foundation (NSF) workshop, several major MEMS packaging and reliability challenges have been identified [11]. They are summarized briefly as follows.

Functional Interfaces: The package provides functional interfaces between the MEMS device and the environment. These interfaces are directly related to the application. Unfortunately (or fortunately), MEMS has a large number of diverse applications as listed above. As a result, a variety of functional interfaces are needed such as optical, RF, thermal (radiation, conduction or convection), fluids (liquids or gases), mechanical (body or surface loadings) and others (e.g. radiation, magnetic, etc.). Clearly indicated by this long list of interfaces, there will be no "standard" packages to meet the requirements of all the MEMS applications. The urgent issue is to identify and develop standard packages for each functional interface. For example, standard optical MEMS packages will be critical to substantially reduce the cost for different MEMS-based optical applications.

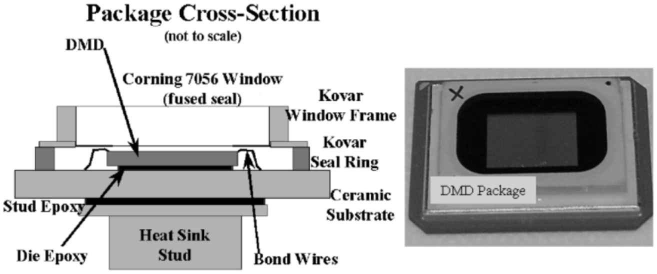

Fig. 3. Package for digital mirror device (courtesy of John P. O'Connor, Texas Instruments).

Reliability: Stiction, fracture and fatigue, mechanical wear with respect to frequency and humidity, and shock and vibration effects are the major causes of MEMS failures. During the last 15 years, MEMS reliability has been improved significantly [9], [12], [13]. The most reliable MEMS devices are hermetically packaged single-point contact or no-contact devices; however, hundreds of novel MEMS devices demonstrated in laboratories demand contacts. For example, surface impact is desirable to achieve a high capacitance ratio, e.g., $\mathrm{C_{on}/C_{off}} = 100$, which is critical to the performance of RF MEMS [14]; however, charge-induced and moisture-induced adhesion problems are difficult to overcome for such surface contacts. With surface contacts, reliability with trillions of impacting or rubbing cycles is needed. In addition, the improved reliability should be accomplished in a nonhermetic package in order to reduce MEMS costs from tens of dollars to cents. No MEMS products are in nonhermetic packages today, although this is always a desirable goal.

Modeling: The package is usually an integral part of the device. Both the device and the package have to be designed at the same time. In order to have a one-pass design, physical and semi-empirical models have to be developed. With such diverse applications, a MEMS computer aided design (CAD) tool needs to cover every engineering discipline: electrical, thermal, mechanical, optical, electromagnetic wave, and chemical. The integration of all the existing tools with innovative interface solutions will be challenging. In addition, how to design reliable MEMS will be as important as the aforementioned tests and the development of new processes/materials. The state-of-the-art CAD tools are being developed to conduct integrated analysis with the consideration of electrical, thermal, mechanical, optical, and electromagnetic wave performance. Such an integrated analysis is very challenging for complex devices and packages. Furthermore, the expansion of microfluidics to new areas calls for the development of new and efficient modeling tools capable of handling fluidic and bio-chemical problems simultaneously.

Integration: As indicated in the Functional Interface challenge, MEMS packaging and reliability is strongly related to the application. In addition, packaging and reliability are strongly related to the device fabrication. For each MEMS product, there is always a critical integration issue to be considered: where and how to integrate the fabrication and packaging processes? Such an integration consideration also provides us an opportunity to create new concepts or technologies for low-cost, high-performance MEMS. For example, wafer-level packaging can be completed in the same fabrication facility, which may eliminate a packaging step. Such a packaging approach will result in low-cost and compact MEMS and is the main development target for most of the MEMS packages being manufactured today [4]. On the other hand, packaging technologies can be used to fabricate MEMS devices and to eliminate another packaging step. Flexible circuit board technologies have been used to develop paper movers and RF MEMS switches [15]. Co-fired ceramics technologies are very popular in the development of micro chemical plants and high-temperature MEMS [16]. In addition, fabrication and packaging technologies can be integrated to form new MEMS. For example, solder technologies have been developed to self-assemble MEMS. The combination of the planar fabrication and the solder self-alignment enables us to develop three-dimensional, complex MEMS without demanding complicated fabrication processes [17].

MEMS packaging challenges are often application-dependent. In order to discuss the challenges in more detail, we will focus on specific devices. In the following sections, we will present two representative MEMS packaging cases. One is for the accelerometer, which is representative of the physical MEMS applications. The other is for BioMEMS, which represents chemical, aqueous MEMS applications. These case studies help us gain further insight into MEMS packaging challenges.

A. Case Study: Packaging for MEMS Accelerometers

Micromachined accelerometers for measuring acceleration are one of the most productive MEMS applications in industry. Today, the sales volume of MEMS accelerometers has been the second largest one next to the pressure sensors since the first device was demonstrated in 1978 [18]. Since it is difficult to measure acceleration directly, the accelerometer device measures the force exerted by the constraints placed on a reference mass to hold its position fixed in an accelerating body. The output is usually an electrical voltage. Fig. 4 shows a two-chip Motorola accelerometer in an industry standard 16-pins dual in-line package (DIP) [19]. Fig. 5 explains the operation of a capacitive accelerometer device. When acceleration occurs, the movement of the proof-mass of the MEMS accelerometer will result in the capacitance change, which can be measured to detect the acceleration.

Based on the law of balance of linear momentum, the mechanical transfer function can be derived as

$$\mathrm{H(s)} = \frac{\mathrm{Z(s)}}{\mathrm{a(s)}} = \left(\mathrm{s}\,.\,\mathrm{s} + \mathrm{s}\,.\frac{\mathrm{D}}{\mathrm{M}} + \frac{\mathrm{K}}{\mathrm{M}}\right)^{-1} \tag{2}$$

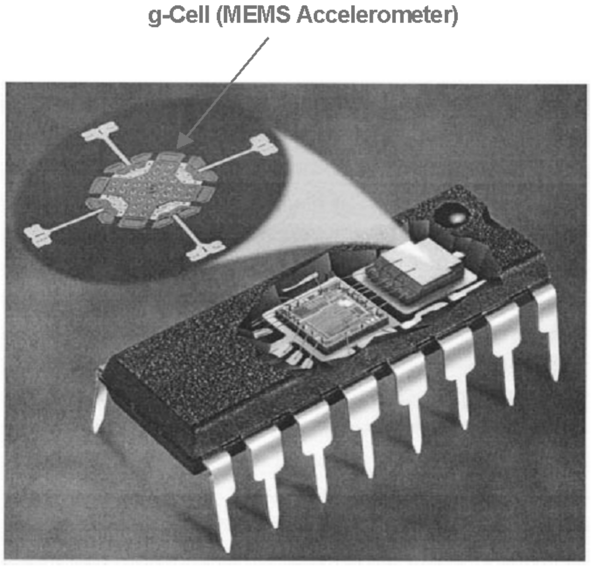

Fig. 4. Two-chip accelerometer in a 16-pin dual in-line package [19].

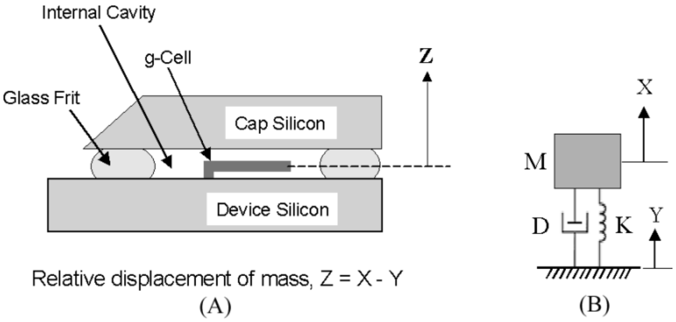

Fig. 5. Schematic [19] and lumped mechanical model of a MEMS accelerometer.

where $\mathrm{s} = \mathrm{j}\omega_\mathrm{n}$; Z = relative displacement of g-cell proof-mass; a = acceleration; D = damping; M = mass of g-cell proof mass; K = stiffness of spring; j = imaginary unit; $\omega_\mathrm{n} = \mathrm{natural\ frequency} = (\mathrm{K}/\mathrm{M})^{1/2}$. The quality factor is

$$\mathrm{Q} = \frac{(\mathrm{M}\,.\,\mathrm{K})^{\frac{1}{2}}}{\mathrm{D}}. \tag{3}$$

The static sensitivity is

$$\mathrm{SS} = \frac{\mathrm{Z_{static}}}{\mathrm{a}} = \frac{\mathrm{M}}{\mathrm{K}} = \omega_\mathrm{n}^{-2}. \tag{4}$$

The noise equivalent acceleration is [20]

$$\mathrm{NEA} = \frac{(4\mathrm{K_B}\,.\,\mathrm{T}\,.\,\mathrm{D})^{\frac{1}{2}}}{\mathrm{M}} = \left(4\mathrm{K_B}\,.\,\mathrm{T}\,.\,\frac{\omega_\mathrm{n}}{\mathrm{MQ}}\right)^{\frac{1}{2}} \tag{5}$$

where $\mathrm{K_B}$ is the Boltzmann's constant and T is the absolute temperature.

The above equations describe the general behavior of an accelerometer. For example, reduced damping could increase Q factor if the mass of the proof-mass and stiffness of the spring remain the same as indicated in (3). Such reduced damping could result from the decreased pressure in the vacuum packaging. It is a challenge to achieve and maintain a very low-level pressure in a vacuum package. Another example is for the reduction of the mechanical noise. As shown in (5), in order to reduce the noise, the mass and quality factor should be increased.

The applications of accelerometers cover a very broad range. For automotive applications, they are used to launch air bags and activate vehicle stability systems and electronic suspension. MEMS accelerometers are also applied in the biomedical industry for activity monitoring. Besides, they are used in various consumer applications, such as active stabilization of picture in camcorders, head-mounted displays, virtual reality, and sport equipment. In industrial applications, they are used for robotics, and machine and vibration monitoring. They are also critical to oil exploration, earthquake prediction, and platform stabilization. In military applications, MEMS accelerometers can be used for impact and void detection and guidance in missiles and other ordnance. High-sensitivity accelerometers are crucial components in self-contained navigation and guidance systems.

Based on the operation principles, MEMS accelerometers can be classified into the following types: piezoresistive, capacitive, piezoelectric, resonant, thermal, tunneling, optical, and electromagnetic devices. The first commercialized MEMS accelerometers were piezoresistive devices; however, the most successful MEMS accelerometers are capacitive devices that are in mass production. The latest development of optical MEMS accelerometers integrates optics and micromachined silicon for high electromagnetic interference (EMI) noise immunity and good linearity. Accelerometers are typically specified by their sensitivity, frequency response, resolution, maximum operation range, full-scale nonlinearity, offset, off-axis sensitivity, and shock survival, etc. Since MEMS accelerometers are used in a wide range of applications, their required specifications are also application-dependent.

A MEMS accelerometer package has to protect the sensing element in various environments without inducing significant stress or drift. Mounting errors or misalignment affecting the sense direction of the device need to be calibrated. For most of the microelectronic packaging, the housing is used to protect the IC from mechanical, chemical, or electrical damage or EMI. For the MEMS packaging, additional considerations are signal sensitivity, linearity, and noise induced by the packaging. For example, for sensor packaging, the accuracy and sensitivity critical to sensing devices can be deteriorated due to thermal mismatch and stress hysteresis. Both metal can and multilayer ceramic hermetic packages have been used to house the sensor and its interface IC. To reduce the cost-to- performance ratio, the sensor and the IC could be packaged at the wafer level with capping glass or silicon wafers bonded to the device wafer, followed by plastic injection molding [21], [22]. In addition, the development of high-precision accelerometers demands more advanced packaging for low-noise, low-temperature sensitivity and high-reliability [23], [24].

B. Case Study: Packaging for Biomedical Microelectromechanical Systems (BioMEMS)

BioMEMS have been developed using a variety of micro-manufacturing methods. These biomedical microdevices, also known as biomedical microsystems, are valuable tools in the health care applications. They facilitate the integration of micro-scale sensors and actuators, microfluidics, micro-optics, and structural elements with computation, communication and control. BioMEMS holds great promise in the areas of precision surgery with micrometer control, rapid screening of common diseases and genetic predispositions, and autonomous therapeutic management of allergies, pain, and neurodegenerative diseases. Successful development of this technology will lead to enormous health care advances, most important of which are early identification of disease and risk conditions, less trauma and shorter recovery times, and more accessible health care delivery at a lower cost.

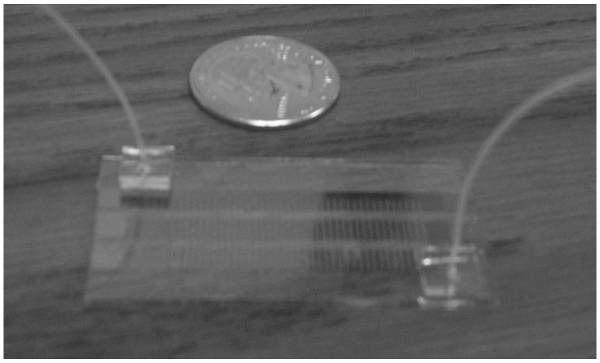

Fig. 6. Semi-disposable PCR system.

Fig. 6 presents an example of integrated BioMEMS, which is a semi-disposable polymerase chain reaction (PCR) system. Its schematic design is shown in Fig. 7. The PCR is used to amplify DNA samples when experiencing thermal cycling of three different temperatures (95 °C for DNA denaturation, 60 °C for primer annealing, and 72 °C for replication). The number of thermal cycles for a continuous-flow DNA sample to pass through determines the efficiency of DNA amplification. The glass substrate provides three temperature zones for the thermal cycling through three on-chip micro-heaters. The glass substrate is biocompatible and allows optical access to the reaction channel to conduct on-line monitoring of the DNA amplification efficiency. The microchannel used for the flow with the DNA sample and reagents was fabricated by micro-transfer molding with polydimethylsiloxane (PDMS). The PDMS part is disposable, but the glass substrate could be reused. The PDMS part was bonded to the glass substrate after oxygen plasma treatment. Loading samples and reagents into the PCR chip is very challenging due to the requirements for biocompatibility, minimum dead volume, mechanical stability, etc. Fig. 8 shows PDMS interconnects developed at the inlet and outlet of the DNA chip. These interconnects were used to connect the microchannel to the external syringe pumps for sample delivery. These interconnects should withstand pressures up to 70 psi (483 kPa).

There are three approaches for BioMEMS packaging: monolithic integration, multi-chip module (MCM), and stacked modular systems. The monolithic integration works well for simple devices or components using same or similar fabrication processes. All components are fabricated on the same substrate for a compact device with minimum manual assembly [25]. MCM bonds the chip to a substrate that offers electrical and fluidic connections, as well as mechanical support [26]. If the device involves any heating effect, the substrate could also be used as

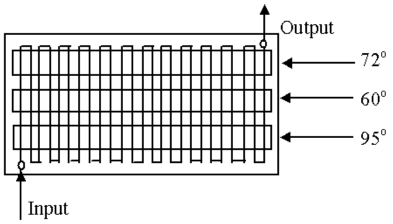

Fig. 7. Schematic design of a semi-disposable PCR device developed by fabricating the microheaters on a glass substrate and the microchannel in a disposable PDMS cover sheet.

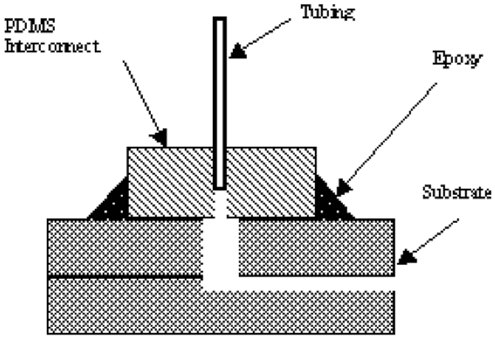

Fig. 8. PDMS-based micro-fluidic interconnect to deliver the DNA sample and reagents to the PCR reaction channel.

a heat sink. The MCM approach offers excellent design flexibility and component-swapping capability. The stacked modular system involves individual components stacked to form a complicated integrated system. Its benefits include excellent flexibility, serviceability, and the possibility to test individual components and dispose a part of the system [27].

At the present time, only a small number of BioMEMS have actually been used in real heath care applications. In addition to a slow approval process and the inertia of the medical industry, the technical barriers are packaging, materials, fluidics, interconnects, reliability, testing, and calibration. The packaging challenges are:

1) biocompatibility, requiring the device and packaging materials not to be toxic to living cells;
2) temperature control, to prevent denaturation of biomolecules at high temperatures;
3) microfluidic, for device-to-device and device-to-macro-components interconnects;
4) electrical connections with isolation between electronics and biofluids, to avoid signal interference and damage to the biofluid;
5) disposability, to prevent transfer or interference of diseases. Any residual biomolecules from previous analysis may interfere with the current one and possibly transfer disease from one patient to another.

III. NEMS PACKAGING

As we mentioned in the introduction, exploration of NEMS fabrication technologies and applications is an active area of research among engineers and scientists across the globe. NEMS technology has the potential to significantly expand the scope of MEMS emerging applications. Most of NEMS-enabled applications are far from commercialization; hence their packaging challenges are difficult to define at the present time. Nevertheless, we envision a two-step, hybrid approach in packaging nano-scale devices. This hybrid approach takes advantage of chemical methods for making the nano-scale device and uses solid-state microfabrication for providing a platform for assembling the device and interfacing to larger-scale components.

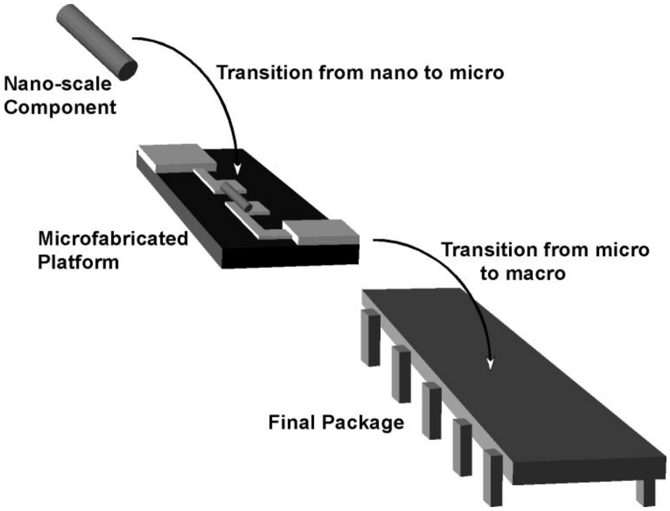

Fig. 9. Assembling and packaging a nano-scale device.

As shown in Fig. 9, the first packaging step is for the transition from nano to micro. In this step, the nano-scale device should be positioned onto a microfabricated platform. This step is necessary since most nano-scale devices are too small and sensitive to be interfaced directly to a macro-sized package. The second packaging step is for the transition from micro to macro. This involves packaging the microfabricated platform and providing the proper connections to the macro-levels.

The second micro-to-macro step is in fact MEMS packaging. All the MEMS packaging challenges mentioned above will be applicable to this step. We note that the requirements for packaging a nano-scale device in this step may be more stringent than the ones for the MEMS counterpart. For example, the micro-resonator shown in Fig. 2 is affected by the package vacuum level. Its nano-scale counterpart, the nano-resonator, will be more sensitive to the vacuum level. The package should maintain an ultra-high vacuum level. NEMS devices enable us to measure very small forces. They are also strongly affected by any undesirable small forces associated with packaging.

The first nano-to-micro packaging step is new and needs more discussion. Placement of a nano-scale object onto a platform is a challenging task. Although scanning probe methods have been employed for manipulating nano-scale objects [28], in general, serial manipulation and placement of nano-scale objects is slow and expensive. Adhesion in the nano-scale also prohibits efficient transfer and manipulation of objects. Self-assembly provides an excellent alternative here. This process is widely applicable in making and assembling nano-scale devices [29]. From supramolecular structures [30] to ordered nanocrystal arrays [31], Self-assembly contributes to making nano-scale objects and devices. Many nano-scale devices are made through synthetic chemical methods. For example, to make the proper molecule for a molecular electronics device, synthetic organic chemistry is used to make the molecule in the bulk form [32]. After the molecules are made, self-assembly can assist in the proper placement of them onto a microfabricated platform.

Self-assembly is a highly parallel method and does not require one-by-one manipulation of components. In a self-assembly scheme, the nano-scale components are designed and produced in such a fashion that they self-assemble in the correct position on the microfabricated platform spontaneously. Surface chemistry can be used to "program" such a self-assembly process. For example, thiol molecules in a molecular electronics device self-assemble onto a gold platform due to the covalent bond between the sulfur atoms in the molecules and the gold atoms on the substrate [33]. This self-assembly process is "programmed" by placing the S-H group in the molecules and providing a gold surface on the microfabricated platform. We anticipate that self-assembly will play a key role in the transition from nano to micro step for packaging nano-scale devices. Self-assembly at the molecular level provides a highly parallel and precise way for manipulating components. Two case studies will be presented to gain an insight into this process.

A. *Case Study: Silicon Nanowire (SiNW) Biosensor*

As an example, we will consider the case of a Silicon Nanowire biosensor [34]. A SiNW that is positioned between two metallic electrodes constitutes the heart of the sensor (Fig. 10). The SiNW is chemically functionalized with different binding sites to provide a recognition mechanism for proteins or antibody-antigens. The binding sites on the wire are specific to the molecule that is targeted for detection. If the target molecule is present in the environment of the SiNW sensor, it will bind to a complementary binding site on the wall of the SiNW. This binding event changes the surface charge density and hence the conductance of the SiNW. The conductance of the SiNW can be monitored electronically and thus, by observing the changes in conductance, the presence of the target molecule can be detected.

In a demonstration of this concept for protein detection, a SiNW was functionalized with biotin by its exposure to phosphate-buffered solution of biotinamidocaproyl-labeled bovine serum albumin. After rinsing, the SiNW contained binding sites for streptavidin and could be used for detecting this protein. As the sensor was exposed to a solution of streptavidin, due to the binding between biotin on the surface of the SiNW and streptavidin, the density of surface charges on the wire changed. This in turn changed the effective conductivity of the wire that was monitored electronically. A correlation curve was developed between the concentration of streptavidin in the environment and the effective conductance of the SiNW. Due to the small diameter of the SiNW, the change in the surface charge density altered the conductance significantly. By using such a nano-scale device, extremely sensitive sensors in the picomolar region were demonstrated.

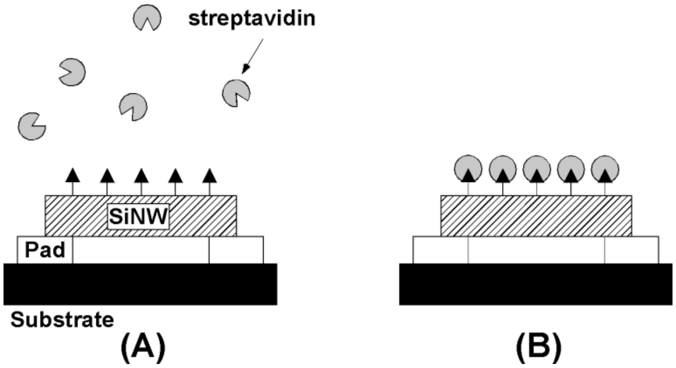

Fig. 10. Operation principle of the sensor is also based on self-assembly. A biotin-functionalized SiNW bridges between two conducting pads. Upon exposure of the SiNW to a solution containing streptavidin, molecular recognition between the molecules in the solution and the surface of the SiNW results in binding and self-assembly of streptavidin onto the surface.

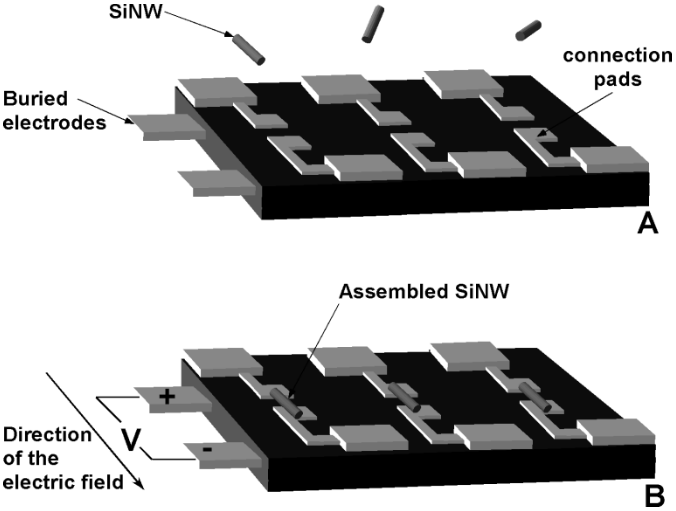

Fig. 11. Using electric-field assisted self-assembly for positioning silicon nanowires (SiNW). The buried electrodes generate an electric field parallel to the surface of the chip that aligns and positions the SiNWs in the correct position.

These SiNWs were synthesized with nanocluster-mediated vapor-liquid-solid growth mechanism [35]. An important problem in making the sensor is positioning the nano-scale wire on the correct electrical pads. This problem can be solved by taking advantage of electric-field assisted self-assembly [36]. In this scheme, two buried electrodes in the chip are used to generate an electric field parallel to the surface as shown in Fig. 11. Nanowires are dispensed onto the surface from a colloidal solution and polarized by the electric field. The electric field on the surface of the chip pushes the nanowires toward the regions of high electric field. This dielectrophoretic force moves and aligns the SiNWs to the electrodes. When a SiNW is aligned to a set of electrodes, the electric field in the vicinity of the wire is reduced and hence, other wires do not align on the same electrode close to the first aligned wire. After alignment, the process can be followed by e-beam lithography and metal evaporation to fix the position of the SiNWs on the chip. In this scheme, the electric field aligns and positions the SiNW in the correct location and hence, without one-by-one component manipulation, a number of SiNWs can be positioned on a chip in a parallel fashion. The rest of the packaging will be similar to packaging of a microfabricated bio-sensor.

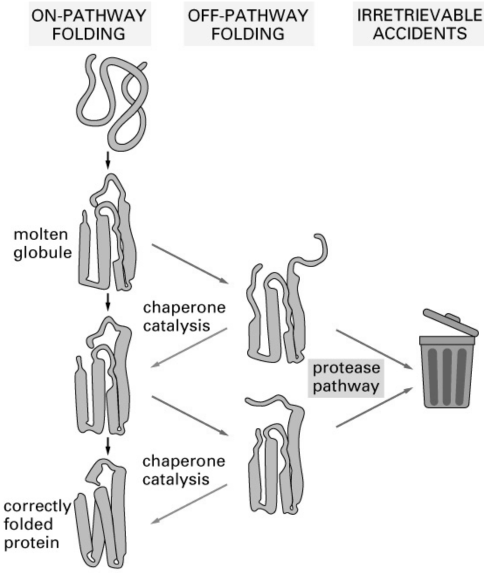

Fig. 12. Correctly folded proteins and correction and removal of incorrectly folded proteins.

B. *Case Study: Self-Assembly in Molecular Biology*

Nature exhibits a range of fascinating self-assembly processes in the nano-scale. One of the most intriguing biological self-assembly processes pertains to the folding of proteins. Millions of proteins, each one acting as a nano-electro-chemical-mechanical device, are responsible for performing many of the vital functions of a living cell. Study of the structure and function of proteins is one of the most active areas of biology and biochemistry.

A protein is a polypeptide chain with tens to hundreds of different amino acids interconnected. There are 20 different amino acids available to form an effectively unlimited number of different combinations. After a chain is synthesized in a ribosome in a cell, it goes through a conformational change (folding). In order for a protein to function properly, it needs to be folded into the proper form. This self-organization process is essential for attaining a useful protein with the correct function. One may consider the folding step reminiscent of “packaging” the protein after it is “fabricated.”

In the folding process the amino acids’ side chains interact with each other through hydrogen bonds, ionic bonds, van der Waals attractions and hydrophobic interactions. As shown in Fig. 12, each protein reaches the precisely folded configuration through an energy minimization process [37]. The error rate to reach another stable configuration is extremely small. When that occurs, the incorrectly folded proteins are detected, and subsequently corrected or destroyed. This folding is a very precise self-assembly process critical to the mass production of proteins, i.e., nano-electro-chemical-mechanical devices, in biological cells.

Protein folding is one of the self-assembly processes in molecular biology. We would like to present another example to illustrate the use of self-assembly to interconnect proteins. Fig. 13 illustrates an interesting application of self-assembly in the protein engineering technology that selects and interconnects specific proteins in a membrane. The technology manipulates hydrophobic and hydrophilic surfaces of a lipid bilayer membrane. As shown at the top of the figure, each lipid bilayer membrane consists of two hydrophilic surfaces facing the outside aqueous environment and two hydrophobic surfaces embedded inside. In order to extract the proteins embedded in the membrane we can use detergent micelles. Each micelle consists of a single layer with one hydrophobic and one hydrophilic surface. The micelles can break the lipid bilayer and solubilize the membrane proteins. The solubilized proteins can then be separated by centrifugation or diffusion processes. We can remove the detergent from these proteins and integrate them with the lipid bilayer again through the self-assembly process. This procedure is a common practice in molecular biology that manipulates proteins through the use of hydrophilic and hydrophobic properties.

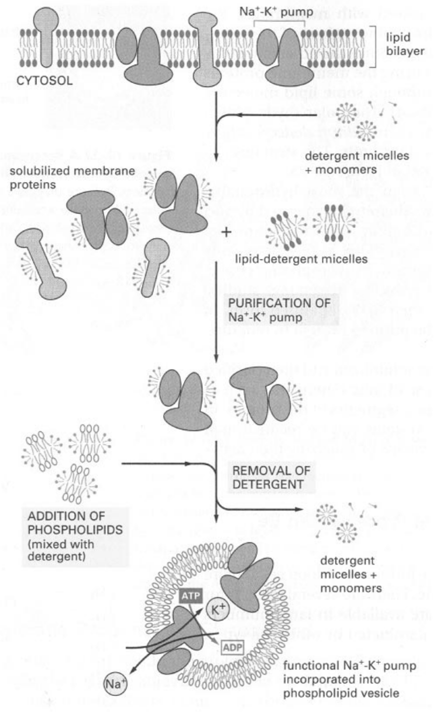

Fig. 13. Proteins purified and reconstituted.

The nano-scale, self-assembly processes occurring in living cells are inspiring and clearly indicate a path for bio-mimetic engineering and packaging of NEMS. We note, however, that mimicking the function and structure of bio-systems is not the only method to proceed in design and fabrication of nano-scale devices and systems.. For example, the electric-field assisted self-assembly process that was discussed for SiNWs does not have a biological counterpart to the best of our knowledge. Energy minimization is the common factor among all the self-assembly processes that we discussed here. It is also the principle responsible for solder self-alignment widely used for microelectronic and optoelectronic packaging. We can perhaps draw a parallel here. In the past number of years, by understanding the physical principles governing solder self-assembly, packaging engineers have amassed an in-depth knowledge of how to apply this technique to various innovative applications for commercial products. In the years to come, with the scaling of the manufactured systems to the micro and nano domains, we anticipate that the packaging community will continue this innovative trend by incorporating new phenomenon and methods. At times, this may require having a glance at other fields such as biology or chemistry. Scaling of packaging techniques from the millimeter-scale to the micro-and nano-scale will be a challenging and certainly an exciting task.

IV. CONCLUSION

Some of the MEMS and NEMS packaging challenges have been described and discussed. MEMS packaging strongly affects the device performance, especially in the case of devices with moving parts. The MEMS packaging challenges are application-dependent. Critical issues belong to the four categories of functional interfaces, reliability, modeling, and integration. In addition to the general discussion, two case studies on accelerometers and BioMEMS have been presented. Accelerometers represent a physical MEMS application and the BioMEMS represents a chemical and aqueous MEMS application.

NEMS packaging challenges could not be defined clearly since most of NEMS devices are exploratory at the present time. Self-assembly of nano-devices is chosen for a detailed demonstration. It was illustrated by a case study on a silicon nanowire biosensor and two examples of self-assembly in molecular biology. Self-assembly is well recognized to be critical to the NEMS packaging. MEMS/NEMS provide new technologies with the societal impact that could rival that of ICs. It is critical to solve the packaging problems and remove the barriers in order to make such an impact real.

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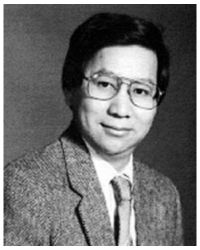

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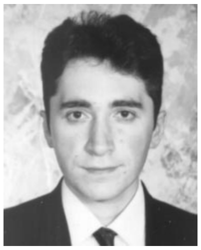

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