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CHALLENGES OF NANOTECHNOLOGIES AND SOME RELIABILITY ASPECTS

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Abstract. The article focuses on the analysis of different nanoelectronic architectures with special design rules, taking into account the reliability of the future product. In the next decade, the reliability will play an even bigger role for industries in *nanofabrication*, which amounts to designing, and manufacturing devices on the nanometre scale. The main thrust in any reliability work is identifying failure modes and mechanisms. This is especially true for the new technology of microelectromechanical systems (MEMS). High reliability is often stressed as an argument for projects in nanotechnology. Despite these claims, only little work has actually been done in the field of reliability in nanotechnology in clear contrast with microelectronics which is now extending its reliability modelling to nanoscaled semiconductor circuits. Nano-manufacturing will provide more twists to the traditional models due to the nature of nano-defects, and Heisenberg uncertainty. Nanotechnology has the potential to create many new materials and devices with wide-ranging applications, such as in medicine, electronics, and energy production. The reliability aspect includes both the electronic and the mechanical parts, complicated by the interactions. The challenging issue in MEMS technology development and commercialization is justifying its reliability. Packaging has often been referred as the "Achilles heel of MEMS manufacturing".

Keywords: *MEMS, NEMS, nano-objects, quantum-dots, nanodevices, nanoelectronics, dominant failures modes, Micro / nanosystem products, reliability, failure analysis.*

1. Introduction

"Nanotechnology[1] is the research, and technology development at the atomic, molecular, or macromolecular levels, in the length scale of approximately 1−100 nm range, to provide a fundamental understanding of phenomena, and materials at the nanoscale; and to create, and use structures, devices, and systems that have novel properties, and functions because of their small, and/or intermediate size". [ROC 01] At this level, the physical, chemical, and biological properties of materials differ in fundamental, valuable ways from the properties of individual atoms, molecules, or bulk matter.

The nanomaterials are nano-objects with at least one dimension smaller than 100 nm. There are materials commercialized for many years, which were not known as nanomaterials, such as: nanoparticles of black carbon, silica precipitate, silica gels or

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[1] The term "nanotechnology" was introduced in 1986 as a result of research from an undergraduate student named Eric Drexler at the Massachusetts Institute of Technology (M.I.T.).

carbonates. The second category of nanomaterials, those nanostructured by design as nanomaterials, is the object of this section. Some examples: nanoparticles (aluminium oxide, colloidal silica, zinc oxide), carbon nanotubes, quantum dots, nanowires and nonporous materials. In many cases (if not in all), the properties of a nanoscale material is different from the micro or macro scale one.

Moreover, the nanostructure properties could be modulated under the action of some stress factors. This was an important research goal in the last years. For instance, for *quantum dots (QD)* of InGaAS (with diameters of 20 nm) processed by a MEMS technique (being included in a air-bridge with a thickness of 0.11 μm), an external stress could be used for modulating the electronic states: by applying an electrostatic force, the number of carriers, the energy levels or the spin configuration could be manipulated [BAB 10].

The design and fabrication of nanodevices is studied by the discipline called *nanoelectronics*. Nanoelectronic architectures are created, with special design rules, taking into account also to the reliability of the future product. These are discrete and integrated devices with much smaller dimensions than in microelectronics, and with specific problems, different from those at the micro level [BHU 10]. An example is given by the *quantum structures*, which are in fact semiconductor devices with the electrons confined in all three dimensions. Another example is represented by the e*lectromechanical systems at nano level* (sensors + actuators + integrated circuits), the so-called nano-MEMS or NEMS (nano-electro-mechanical-systems), similar to MEMS, but smaller, which include also devices for microfluidics or biocompatible ones, for biomedical applications (Figure 1).

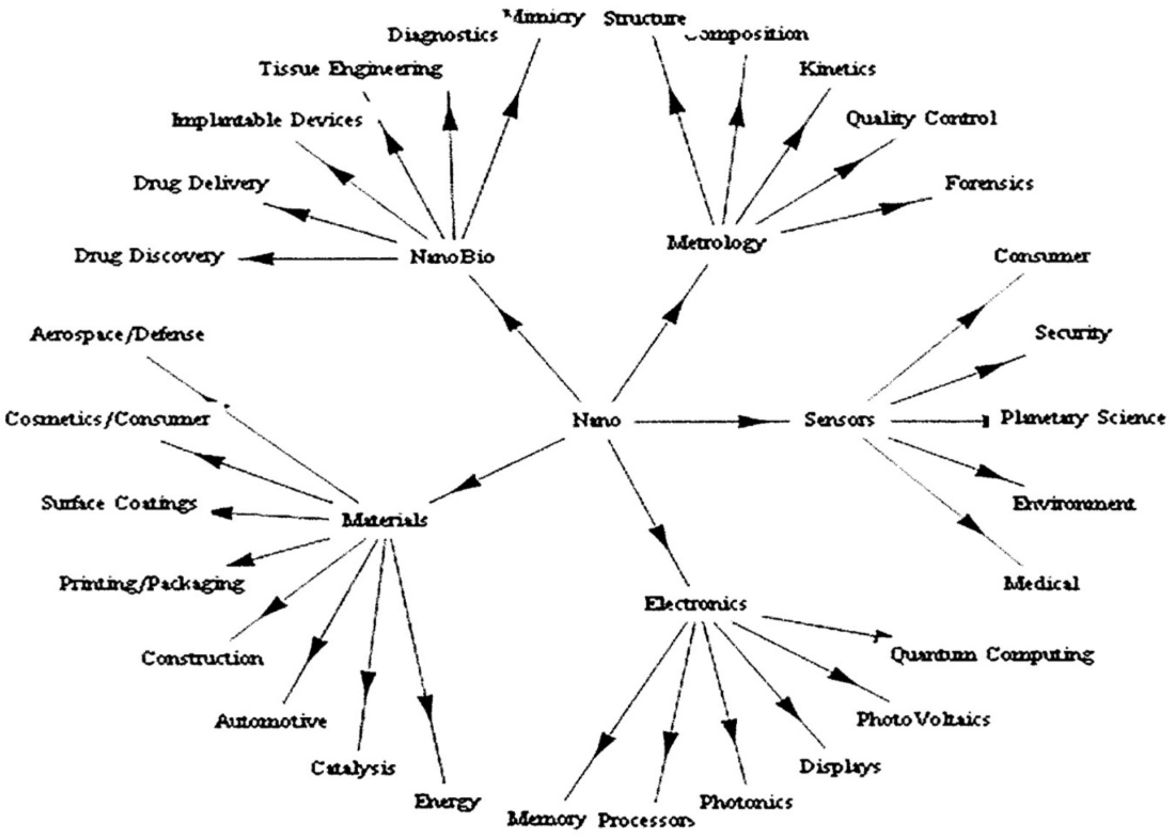

Figure 1. Schematic of nanotechnology application areas. (Source WikiMedia Commons, P. Fraundorf, distributed under the Creative Commons Attribution-Share Alike 3.0 Unported license).

In 2000, the first very large scale integrated (VLSI) NEMS device was demonstrated by researchers from IBM. In the next decade, the reliability will play an even bigger role for industries in *nanofabrication*, which amounts to designing, and manufacturing devices on the nanometre scale. On the molecular level, familiar material properties like conductivity no longer obey laws based on macro scale materials (e.g., Ohm's law). In the same sense, the essential metrics of reliability analysis such as material degradation, fatigue, and basic failure mechanisms assume new meaning on the nanometre scale.

The main thrust in any reliability work is identifying failure modes and mechanisms. This is especially true for the new technology of microelectromechanical systems (MEMS). The methods are sometimes just as important as the result achieved. One methodology uses statistical characterization and testing of complex MEMS devices to help to identify dominant failure modes; test structures designed to be sensitive to a particular failure mechanism are typically used to gain understanding, and the development of predictive models follows from the basic understanding.

For a final product, all aspects of fabrication, packaging (Figure 2), system integration, and manufacturing must be considered. It is important to acknowledge that there can be failure modes associated with friction, for example, a high static friction coefficient that prevents operation of the device, or an increase in dynamic friction with age such that drive signals designed at the time of fabrication are in some later time insufficient to operate the device. It should also be noted that friction and wear are coupled phenomena, since friction provides the shear force at the surface necessary to cause material damage and removal, and this material damage will influence the subsequent friction forces. Device and test structure data are shown that reveal the basic understanding needed to develop a predictive reliability model [TAN 01].

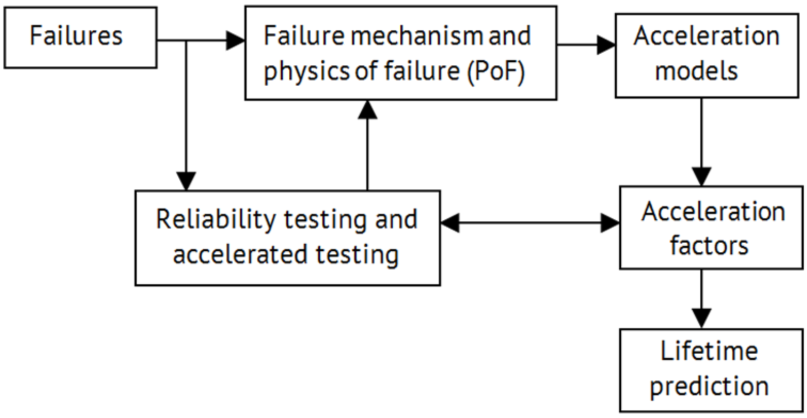

Figure 2. Life time prediction diagram.

Reliability is one of the main properties of products in a safe and sustainable environment in addition to performance, cost and ecological impact. High reliability is often stressed as an argument for projects in nanotechnology. Despite these claims, only little work has actually been done in the field of reliability in nanotechnology in clear contrast with microelectronics which is now extending its reliability modelling to nanoscaled semiconductor circuits. An example is the modelling of time to breakdown of gate oxides with a thickness of 1 to 5 nm due to charge trapping of lattice defects. Classical reliability models may be insufficient due to quantum effects and thermal and defect diffusion processes. Reliability estimates of molecular, solid state or any other system with nanosized functional elements have to consider thermal fluctuations, quantum statistics and

Heisenberg uncertainty relations resulting in contradicting requirements for minimum energy level separation of states, operation frequency and packing density. Nano-manufacturing will provide more twists to the traditional models due to the nature of nano-defects, and Heisenberg uncertainty. For a complex system with a large number of individually functional unit cells their reliability must be very high for the system to ever be operational or redundancies have to be built in which should be more efficient than just operating larger ensembles. To maintain redundant information in a system where the phase of quantum states has to be considered is an unsolved problem, although procedures have been proposed to copy information without decoherence of the wave function as required for redundant storage in quantum computing.

There has been much debate on the future of implications of nanotechnology. Nanotechnology has the potential to create many new materials and devices with wide-ranging applications, such as in medicine, electronics, and energy production (Figure 3). On the other hand, nanotechnology raises many of the same issues as with any introduction of new technology, including concerns about the toxicity and environmental impact of nanomaterials, and their potential effects on global economics, as well as speculation about various doomsday scenarios. These concerns have led to a debate among advocacy groups and governments on whether special regulation of nanotechnology is warranted.

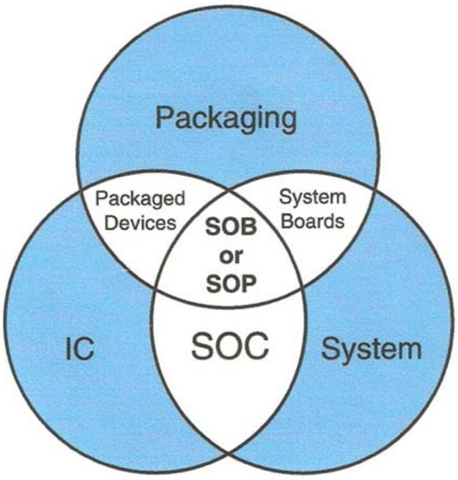

Figure 3. Integration of IC packaging and system.

FA provides understanding of the failure mechanism and the possible root cause. These will in turn help to provide possible solutions to resolve the failures. As a result, production yield and product reliability can be improved. This will indirectly reduce production cost and improve profit margin.

2. The advent of 3D technology

Reliability is of concern if micro-electro-optical-mechanical systems (MEOMS) / micro-electro-mechanical systems (MEMS) machinery is used in critical applications. MEMS are usually a combination of electronic circuits and micro-machinery (Figure 4). The reliability aspect includes both the electronic and the mechanical parts, complicated by the interactions. Different from mechanical systems, inertia is of little concern; the effects of atomic forces and surface science dominate. Wafer level reliability (WLR) has received increasing interest in recent years. We still have limited knowledge on how MEMS/MEOMS devices fail. Limited tools and models are available. How to model the reliability of MEMS/MEOMS is a challenge.

The friction forces at micromachine contacts are difficult to explore with complex devices; consequently, the sidewall friction structure should be designed to permit quantitative measurement of friction forces and to simplify the contact geometry so that observations could be associated with a known contact pressure in an isolated region of the surface. The device should be used to examine the performance of surface treatments, effects of environment, contact pressure, interfacial velocity, etc.

Wear in a confined space such as the gap in a pin joint is a very complex problem. The majority of works on the formation and the role of wear debris / particles is normally performed on "open" sliding systems; in these tests, wear particles are not trapped. It was found that agglomeration of wear particles in bearings increased the normal load of the contact point, leading to seizure.

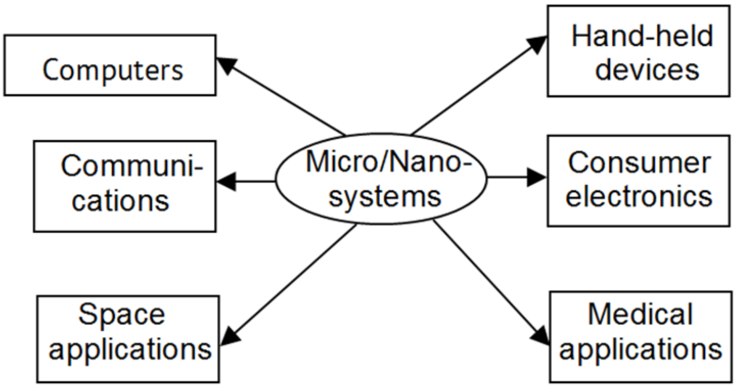

Figure 4. Micro/nanosystem products.

The advent of precision three-dimensional micromachining technologies in the last couple of decades has seen the birth of an exciting and potentially revolutionary field called MEMS (micro-sized devices fabricated by silicon foundry-like process). MEMS are the integration of mechanical elements, sensors, actuators and electronics on common silicon substrate through the utilization of microfabrication technology. MEMS promise to revolutionize nearly every product category, thereby, making the realization of complete system-on-a-chip (SoC). Since MEMS devices are manufactured using batch fabrication techniques, similar to ICs, unprecedented levels of functionality, reliability, and sophistication can be placed on a small silicon chip at a relatively low cost. MEMS technology is enabling new discoveries in science and engineering such as the polymerize chain reaction (PCR) microsystems for DNA amplification and identification, the micromachined scanning tunnelling microscopes (STMS), biochips for detection of hazardous and selection, and so on. This extraordinary unification of functions includes both energy and matter; motion, sound, atoms, molecules, light, radio and other electromagnetic radiation. The blending of attributes from so many diverse fields of science into a single structure is what gives MEMS such incredible power and wide-ranging potential. We can also add one more extremely important science and technology to MEMS, and that is optics. We can call the result optical MEMS or MOEMS (Micro-Opto-Electro-Mechanical Systems). Light control will be the master key that opens up efficient photonics. MOEMS appears poised to be the winner in the realm of light switching and routing. So as the light wave highway moves from the present long haul, or backbone, and approaches fibre-to-home (FTH), we can expect the volume of MOEMS assemblies to increase geometrically.

Now, we have combined essentially every region of science onto and into a single microcosm.

Highly complex devices that can be built by familiar semiconductor mass processes to produce the long-sought System on a Chip (SoC). Close attention should be given to follow the trends of new failure mechanisms in order to prevent them from becoming the bottlenecks in tomorrow's ICs. Computation, analysis and central control of these input/output functions results in a fully integrated system of incredible versatility. Some MEMS devices send and receive light beams; others detect specific molecules, including pathogens and even such complex structures as DNA.

MEMS electrical components include inductors, capacitors, and switches, but MEMS are also being used as arrays of micromirrors[2]. The promises and shortcomings of MEMS switch technology have become almost legendary. Perhaps no other electronic component in history has been the source of so much hype — and the cause of so much disillusionment. Fortunately, the troubling early days are finally over and MEMS switches are rapidly fulfilling all of their earlier promise. As a result, the failure mechanisms of MEMS are a function of both electrical failure (surface or air gap breakdown) and mechanical failure (creep, fatigue, wear, and stiction). Electrical failures can be related to changes in the device's DC or AC parametrics or leakage current. Today, not all ESD failure mechanisms have been demonstrated in all MEMS applications [VOL 09].

The challenging issue in MEMS technology development and commercialization is justifying its reliability. The reliability issues of MEMS devices are more than a simple combination of electrical reliability, material reliability and mechanical reliability. Fabricating multiple devices on the same chip will have to deal with more failure modes. Complex interactions of cross-domain signals, interference and substances induce new failure modes. The device performance of MEMS inertial sensors - such as accelerometers and gyroscopes - is strongly influenced by the stress developed in the silicon die during packaging processes. This is due to the die warpage in the presence of the stress.

MEMS devices are difficult to passivate since they often have moving elements. Coating MEMS devices with passivation materials could change the characteristics of sensors or even prevent motion of parts. Optoelectronics devices are also challenging since they are typically constructed from compound semiconductors that are more reactive and sensitive to a broader range of contaminants.

Another important challenge issue in achieving successful commercial MEMS products is associated with MEMS reliability. Reliability and qualification can be much more complex than for ICs. Many of the MEMS/MEOMS failure mechanisms are not yet well understood. This lack of understanding presents a challenge in developing practical qualification techniques for MEMS products. For the world of ICs there are industry standards tools and techniques for understanding and quantifying the reliability. For the world of MEMS this knowledge base is much more limited. In many cases, companies that do have a firm grip on techniques for quantifying reliability view that knowledge as a competitive advantage and are hesitant to share it. In order to develop reliable MEOMS devices, reliability must be considered at the earliest stages of product development. Decisions made in the design stage can result in devices that will never be reliable. Reliability must be understood at a fundamental physical and statistical level. That is often a perspective that by there very nature MEMS will be unreliable because they have moving parts. The truth is this: it is no moving parts that kill reliability, but rubbing surfaces. MEMS can be designed with moving surfaces, but no rubbing parts, and can be very reliable. Avoiding rubbing surfaces is one of the key elements in achieving reliable MEMS devices [BAJ 09]. Environmental parasites (such as feed through capacitance, eddy currents and molecular contaminants) are identified as major performance limiters for RF MEMS. The reliability of RF MEMS remains

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[2] Some products, like Texas Instruments DMD^{TM} (Digital Mirror Device), send and receive light beams, others detect specific molecules and some deal with several "senses" all at once. If the logic device is the brain, MEMS adds the eyes, noise, ears and other sensory input. But MEMS is also control, the hands and fingers because these devices can move their own parts but also nearby objects and materials. MEMS, while hyped by the media, can more than meet expectations for marvellous micromachines during the next decade. The merging of motion, sensing and computation represents a major leap in technology.

an issue of concern slowing down the commercialization of these systems. In general, the smaller the actuator, the smaller its force becomes, but measurement of such small force is difficult and dependable instruments are not currently available.

3. Device shrinking

Failures can occur at all stages of development, production and end users' sites. With every technology node that results in smaller geometries, the incidence of failures increases significantly. Failures are caused by failure mechanisms, which can be expected to be an order of magnitude smaller than the functional elements themselves. Therefore failure analysis (FA) of today state of the art microelectronics and MEMS devices already require nanotechnological methods. Broad micro-analytical capabilities (SEM, ESEM, AFM, STM etc.) with focused ion beam (FIB) and transmission electron microscopy (TEM) are necessary to cover future requirements. Recently, by device shrink (fineness and miniaturization) and structure complexity, there is further difficult failure analysis of the semiconductor devices. Above all, it is cleared with the device shrink to differ unfair areas obtained by failure diagnosis and failure position analysis from magnitude of areas on physical analysis. Hence, aiming at specification of more detailed failure positions, the Hitachi High Technologies, Ltd. attempted to develop an extremely fine SEM type mechanical proving system [MUN 06]. For this development, there were investigated a high precision probe and stage mechanism corresponding to the fine devices, a six-probes mechanism expandable to applications such as inverter testing, high precision unit transistor testing, and so on, an in-vacuum probing and sample exchanging mechanism to realize high through-put, and a CAD (computer aided design) navigation system. As this system was enough applicable to 65 nm devices, it seems to be possible to apply it to device thereof in future.

As more than Moore are expected in semiconductor domain for near future, challenges for FA in next few years will be extended to a broad new aspects (design for analysis or design for test, physical limit – tools for chip, tools for package, chip-package co-design, and organizational issues like FA cost, and FA cycle time).

4. Carbon nanotubes

Carbon nanotubes (CNT) have properties which make them extremely promising for nanoelectronics, because they undergo better to electromigration than the majority of the conductors used in microelectronics (Al, Cu, Ag, etc.). Today, the existing problems in manipulating CNT and the lack of accurate results from reliability tests still obstruct the use of CNT in commercial products. For instance, there are papers claiming CNT may support without any problems current densities larger than 10^8A/cm^2, even at temperatures of 250^{o}C; other papers report CNT failures after seconds of functioning at room temperatures and similar current densities. However, CNT are among the most promises materials for the next generation of nanosystems.

Carbon nanotubes have unique mechanical and electrical properties. For example, they have a yield strength that is 100 times that of steel and they can be either semiconducting or metallic, depending on their geometric structure [KJE 07]. These special properties have led to the fabrication of for example sensors and transistors. Here, the possibility is explored of using a multi-walled carbon nanotube instead of a microfabricated silicon sensor as a strain gauge in a microcantilever-based sensing system. For this purpose, a 3-D micro- and nano-manipulation set-up has been constructed, which can be used for integration of nano-components in prefabricated microsystems during the prototyping phase. Using this set-up, individual carbon nanotubes have been integrated in microcantilever systems and characterized. A small part of the investigated sensors had sensitivity comparable to or larger than that of similar silicon sensors; however, there are significant variations in performance and large intrinsic noise caused by the minute size.

5. Packaging and fabrication

Packaging has often been referred as the "Achilles heel of MEMS manufacturing" and a key bottleneck in the process of MEMS commercialization (Figure 5).

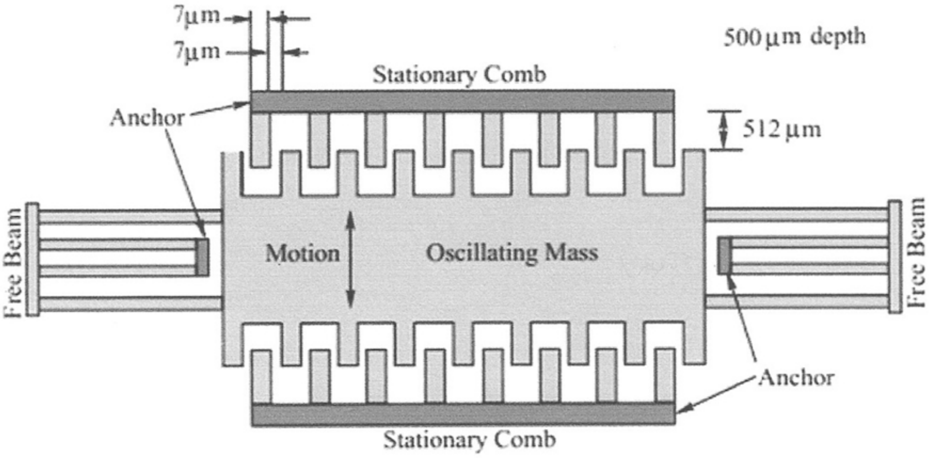

Figure 5. MEMS-based electrostatic transducer (after [MEN 01]).

Other than the few fully commercialized products (i.e. air bag triggers, ink-jet print-heads, pressure sensors and a few medical devices), packaging constitutes the single largest element of cost and a major limitation to the miniaturization potential [GER 09]. No MEMS product is complete unless it is fully packaged. At present, packaging is one of the major technical barriers that has caused long development times and high-costs of MEMS products. Packaging involves bringing together *(i)* multitude of design geometries of the various constituent parts, *(ii)* interfacing diverse materials, *(iii)* providing required input/output connections, and *(iv)* optimisation of all of these for performance, cost and reliability. On the other hand, reliability depends on *(1)* the mutual compatibility of the various parts with respect to the desired functionality, and *(2)* the designs and materials from the standpoint of long-term repeatability and performance accuracy. Reliability testing provides techniques for compensation, and an understanding of the catastrophic failure mechanisms in microsystems [VOL 09][MUN 06]. Engineers cannot design reliable MEMS without first to understand the many possible mechanisms that can cause the failure of the structure and performance of these devices and systems. And design alone cannot ensure the reliability of the product. It is imperative that the successful design and realization of microsystems or MEMS products must include all levels of packaging and reliability issues from the onset of the project. Besides fabrication related issues, packaging encompasses several other aspects that have also affected the overall manufacturability of MEMS devices. These include; *(i)* functional interfacing of the device and their standardisation; *(ii)* reliability and drift issues; *(iii)* hermetic sealing techniques; *(iv)* assembly and handling techniques; and *(v)* modelling issues.

A further challenge is to fabricate more devices than manipulation can facilitate. For this purpose, a parallel integration method is required that can facilitate wafer scale fabrication. This could be in-situ growth, where the nanotube is synthesized from a catalyst particle that already has been placed at the desired position in the microsystem. This has been investigated by developing and fabricating microsystems with integrated catalyst particles and by constructing and optimizing a chemical vapour deposition system for nanotube growth [KJE 07]. The fabrication techniques are essentially two dimensional while the third dimension is created by layering. MEMS components by their very nature have different and unique failure mechanisms than their macroscopic counterparts.

In comparison to electronic circuits, these failure mechanisms are neither well understood nor easy to accelerate for life testing. It is imperative that the successful design and realization of microsystems or MEMS products must include all levels of packaging and reliability issues from the onset of the project. Besides fabrication related issues, packaging encompasses several other aspects that have also affected the overall manufacturability of MEMS devices. These include; *(i)* functional interfacing of the device and their standardization; *(ii)* reliability and drift issues; *(iii)* hermetic sealing techniques; *(iv)* assembly and handling techniques; and *(v)* modelling issues.

6. Critical dimensions

The scanning electron microscope (SEM) as applied to critical dimensions (CD) metrology and associated characterization modes such as electron beam-induced current and cathodo-luminescence (CL) has proved to be a workhorse for the semiconductor industry during the microelectronics era. The work [MYH 08] reviews some of the challenges facing these techniques in light of the silicon nanotechnology road map. Some new results using voltage contrast imaging and CL spectroscopy of top-down fabricated silicon nanopillar / nanowires (<100 nm diameter) are presented, which highlight the visualization challenge. However, both techniques offer the promise of providing process characterization on the 10-20 nm scale with existing technology. Visualization at the 1 nm scale with these techniques may have to wait for aberration-corrected SEM to become more widely available. Basic secondary electron imaging and CD applications may be separately addressed by the He-ion microscope.

Nanotechnology is predicted to create the sixth Kondratieff period following the "Age of information". It represents a new revolutionary approach in fundamental research moving from a macrocentric to nanocentric system. Nanotechnology is expected to stimulate 1 trillion dollars of production involving about 2 million workers in the next 10 to 15 years. More than 40 countries now have specific nanotechnology research funding programs with the common goal of finding greater uses for the emerging technologies and enacting measures to encourage commercialization [MAR 07].

7. Safety of environmental, health and safety (EHS)

Not only do new products based upon nanotechnology result in an ever-increasing sophisticated business economic model, but the new regulatory efforts will mean growth in both products and services devoted to safety of environmental, health and safety (EHS) from the existence of nanotechnology products. From the literature the rate of growth/change is increasing over time. Major advances are occurring in cycles as short as five-years or less. It will not be long until the early products with nano-materials become obsolete. At that point consideration must be given to a safe way to either dispose of or recycle the obsolete nano product. At that time even further commercial opportunities will become present for a nanotechnology garbage collection service or nanotechnology recycling line of business [MCC 08]. In recent years, nanoscience and nanotechnology have attracted much attention and have posed much significant potential in many areas of societal interest. For instance, opportunities are presented to help solve global energy needs with environmentally clean solutions, increasing the quality of life through improved medicine and health care, improving the productivity of agriculture industry, and providing benefits of information technology everywhere. Recent development of nanomaterials has enabled ever-clean cloths and nano-biosensor devices. Nano-electro-mechanical systems (NEMS) in concert with nanoelectronics would help develop intelligent nano-robots for unique applications [KAN 06]. Although serial, robotic assembly methods for nanoscale biosensors such as pick-and-place have allowed significant manufacturing feats; self-assembly is an attractive option to tackle packaging issues.

8. Evaluating the reliability

Two procedures were proposed for evaluating MEMS reliability [BAZ 09]: *(i)* To evaluate the reliability of a Virtual Prototype, i.e. simulating the dependence of the reliability level on device structure and process parameters; *(ii)* To shorten the test time by using accelerated testing, which means to test the components at higher values of stress as those encountered in normal functioning, in the aim to shorten the time period necessary to obtain significant results **(**Figure 6**)**.

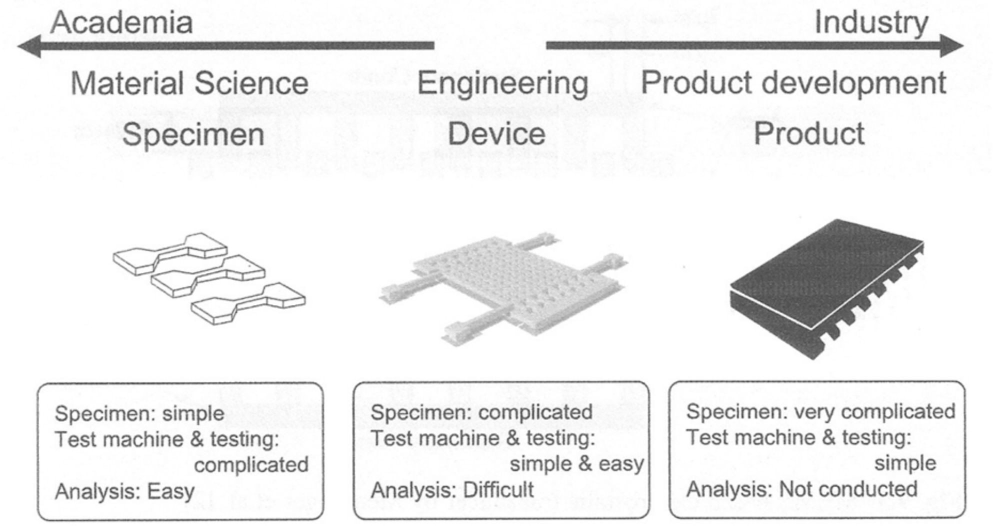

Figure 6 Three levels of reliability evaluation methods.

These two solutions are complementary, because the estimations made on a Virtual Prototype has to be verified by the accelerated testing [BAJ 20].

9. Instead of conclusions

The behaviour of nano-scaled products is much more sensitive to changes in material compositions, manufacturing controllable variables, and noise parameters.

The ultimate goal of manufacturing is to produce functional chips at continually higher volume and lower cost. Improvements in functional volume can be achieved by increasing wafer size, by decreasing die size through decreased critical dimensions, or by designing ICs for manufacturability with an eye toward a reduction in critical area. However, the most productive method is by improving the total die yield[3]. There are only four basic

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[3] Die yield is the percentage of total die successfully manufactured, from silicon processing all the way through packaging and testing. Die yield is a function of manufacturing yield, test yield, package yield, and occasionally burn in yield. Since test, package, and burn in yield are typically close to unity, the die yield effectively becomes the manufacturing yield. For a given technology, reductions in defect

operations required to produce an IC: layering, patterning, doping, and heat treatment. In modern IC processing these four steps are repeated in over two hundred discrete processing steps in an infinite number of combinations, and each one of these steps are potential defect contributors that can reduce the total yield. One estimates to suggest that particles are responsible for 75% of total yield loss in volume IC manufacturing [SHU 02]. Defect inspection, defect classification, and defect source identification are a crucial part of every modern IC fabrication. By necessity, advances in particle detection technology have kept pace with overall technology development.

FA plays a very important role in the semiconductor industry in enabling timely product time-to-market and world-class manufacturing standards. Today ICs contain transistors having minimum geometries of 90 nm, but the industry is now rapidly moving into the 65 nm technology node. The actually chips contain hundreds of millions of transistors and operate at frequencies greater than 5 GHz. In general, the investigation of failures is a vital, but complex task.

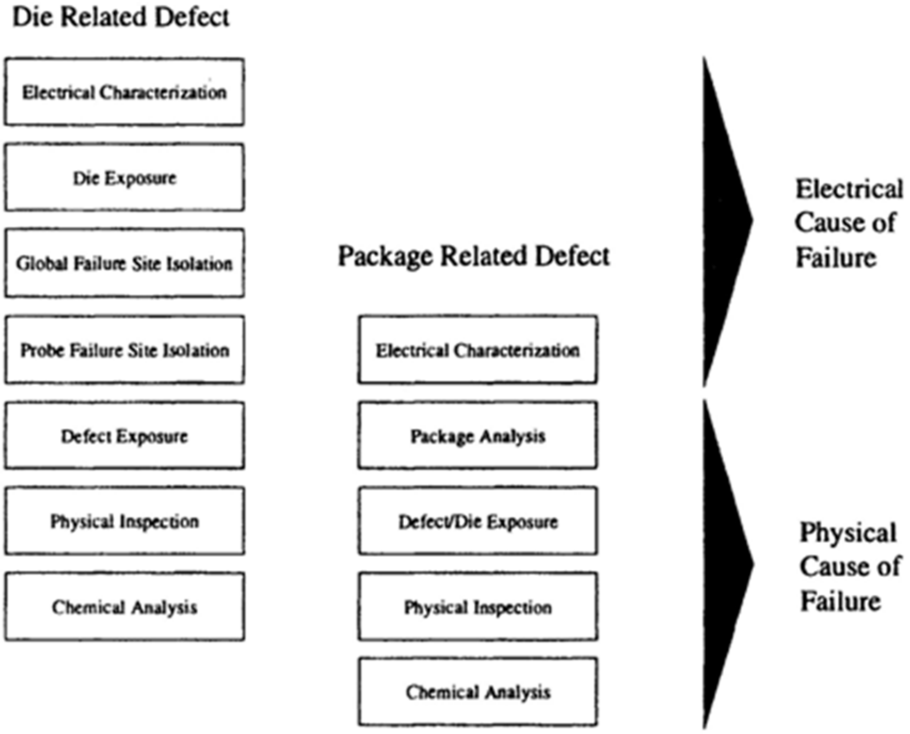

Figure 7 Typical failure analysis process flows for die related and package related defects are shown for comparison. Each flow can be broken down in to an electrical cause of failure determination and physical cause of failure determination.

From a technical perspective, failure can be defined as the cessation of function or usefulness. It follows that FA is the process of investigating such a failure (Figure 7). FA is an investigation of failure modes and mechanisms using optical, electrical, physical, and chemical analysis techniques. A number of tools and techniques enable analysis of circuits where, for example, additional interconnection levels, power distribution planes, or flip chip packaging completely eliminate the possibility of employing standard optical or voltage contrast FA techniques without destructive deprocessing. The defect localization utilises

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density improve manufacturing yield. As technologies shrink, feature sizes decrease, and as feature sizes decrease, the size of a defect that can cause a functional failure decreases as well.

techniques based on advanced imaging, and on the interaction of various probes with the electrical behaviour of devices and defects.

The reliability of MEMS can be extremely sensitive to the environmental conditions, which translates in very stringent demands for the design, the materials used, and the package. Reliability must be built into the device at the design and manufacturing process stages. In most practical cases, the final damage quite rarely reveals a direct physical failure mechanism; often the original cause (or complete scenario of failure) is hidden by secondary post damage processes. On the other side, it is impossible to eradicate failures during the manufacturing process and at field use. Therefore, FA must be performed to provide timely information to prevent the recurrence of similar failures. Or, wafer fabrication and assembly process involves numerous steps using various types of materials. This, combined with the fact that devices are used in a variety of environments, requires a wide range of knowledge about the design and manufacturing processes. This explains while FA of semiconductor device is becoming increasingly difficult as VLSI technology evolves toward smaller features and semiconductor device structures become more complex. Since it is usually not possible to repair faulty component devices in a VLSI, each device in a chip can become a single point of failure unless some redundancy is introduced. Therefore, VLSIs have to be designed based on the characteristics of worst devices rather than those of average devices. Even if a chip is equipped with some redundant devices, today's scale of integration is becoming so high, that the yield requirement is still very severe. The final chip yield is governed by the device yield. A recent research paper [AMA 02] demonstrates that once the major cause of failure is somehow identified or assumed, one could use a Monte Carlo method to study yield problems. Unlike Monte Carlo methods, it produces accurate results even when the probabilities of interest differ from one another by many orders of magnitude. The method proposed in [AMA 02] was applied to the analysis of the leakage current distribution of double-gate MOSFETs; the microscopic failure mechanism was identified that limits the final yield. It explains experimental data very well. The insight into the failure mechanism gives clear guidelines for yield enhancement and facilitates device design together with the quantitative yield prediction. It is useful for yield prediction and device design. Transistors should be designed such that I_t (the maximum current generated by a single trap) is very much lower than the tolerable leakage current at the specified cumulative probability. The method does not have any convergence problems, as in the conventional Monte Carlo approach.

As long as aggressive designs are produced on cutting edge new manufacturing processes, there will be designs that don't work perfectly the first time on silicon or have low yields. Diagnosis and fail mode analysis by themselves can not complete the root cause process. Even if designs worked first time on silicon with reasonable yields, economic consideration of higher profitability, time-to-market and larger market share will drive continuous improvement of product performance, faster manufacturing ramps and higher yields. The question is: how to make the whole process of root-causing failures better, faster and cheaper? FA has implications on investment, required skills of the analyst, lab organization and time to result; the resulting cost explosion in FA cannot be compensated by any conceivable measures to enhance FA productivity, but this suppose that a rising number of today's FA problems will be solved by modern testing techniques. FA becomes such a substantial cost factor in yield learning, that testing must be empowered to do the FA job as well. It is important to integrate FA in semiconductor product and technology development and to introduce it as part of all new projects. This explains while, in the future, analysis productivity will be a key issue for product cost reduction [BOI 99]. More reliable electronic systems with high integrated functionality within a shorter period of development time, new methods/models for reliability of components and materials, and lifetime prediction are necessary. Reliability assurance has to be continued during the production phase, coordinated with other quality assurance activities. In particular: for monitoring and controlling production processes, item configuration, in process and final tests, screening procedures, and collection, analysis and correction of defects and failures. The last measure yields to a learning process whose purpose is to optimise the quality of manufacture, taking into account cost and time schedule limitations.

Today, FA is the key method in reliability analysis. It is impossible to conceive a serious investigation about the reliability of a product or process without reliability analysis. The idea that the failure acceleration by various stress factors (which is the clue of the accelerated testing) could be modelled only for the population affected by a single failure mechanism greatly promoted FA as the only way to separate these population damaged by specific failure mechanisms.

A large range of methods are now used, starting from the (classical) visual inspection and going to such expensive and sophisticated methods as Transmission Electron Microscopy or Secondary Ion Mass Spectroscopy, etc.

A prognostic about the evolution of FA in the next 5 years is both easy and difficult to be made. Easy: because everyone working in this domain can see the current trend. Now the FA is still in a "romantic" period, with fabulous pictures or smart figures smashing the customers, convinced by such a "scientific" approach. Seldom, these users of electronic components do understand the essence of the FA procedure, because the logic is frequently missing. But this situation is only a temporary one. Very soon, the procedures for executing FA will be stabilized and standardized, allowing to any user of an electronic component to verify the reliability of the purchased product.

It is also difficult to predict the evolution of FA [BAB 10], because the continuous progress in micro-electronics and microtechnologies makes almost impossible to foresee with maximum accuracy the types of electronic components that will be most successful on the market. And the FA must serve this development, being one step ahead and furnishing to the manufacturers the necessary tools for their researches.

However, with sufficiently high probability one may say that the nanodevices (or even nanosystems) will become a reality in the next 5 years, so we have to be prepared to go deeper inside the matter, with more and more expensive investigation tools.

Recent advances in the design of MEMS have increased the demand for more reliable microscale structures. Although silicon is an effective and widely used structural material at the microscale, it is very brittle. Consequently, reliability is a limiting factor for commercial and defence applications. Since the surface to volume ratio of these structural films is very large, classical models for failure modes in bulk materials cannot always be applied[4].

The reliability of MEMS is directly related to the occurrence and severity of failures occurring at the manufacturing, operation of the device. It is surprising that little has been done to fully classify these failures. A methodology is also proposed in [KAN 06] to assess their severity and high level design of failures is implemented in the case of a thermal actuator. As the design of MEMS devices matures and their application extends to critical areas, the issues of reliability and long-term survivability become increasingly important.

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[4] For example, whereas bulk silicon is immune to cyclic fatigue failure, thin micron-scale structural films of silicon appear to be highly susceptible. It is clear that at these size scales, surface effects may become dominant in controlling mechanical properties.

Packaging of MEMS is an art rather than a science; the diversity of MEMS applications places a significant burden on packaging [GER 09] (standards do not exist in MEMS packaging).

MEMS will open up a broad new array of cost-effective solutions only if they prove to be sufficiently reliable. It is not clear if standardization of MEMS fabrication process à la CMOS will ever happen - and is even possible. But currently most of the cost for MEMS component happens during back-end process, thus it is by standardizing interfaces that most savings can be expected.

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