Gerald Gerlach · Klaus-Jürgen Wolter *Editors*

Bio and Nano Packaging Techniques for Electron Devices

Advances in Electronic Device Packaging

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Preface

Electronics is more and more dominating our daily life. Computers provide our entry to internet and, hence, the world's largest storage of knowledge, cell phones connect us to relatives, friends and business partners, electronics is more and more controlling every function of our automobiles, and electronic automation technology supports efficient production of goods and is a reliable "partner" in health care. This process of evolution of electronics started in the twentieth century but has been radically accelerated with the occurrence of microelectronics after the transistor was invented in 1947 and the first integrated semiconductor circuit was built in 1958. The world-renowned Moore's law describes this long-term trend in the development of microelectronics that the number of transistors that can be placed on an integrated circuit doubles approximately every eighteen months. Now, this trend has continued for more than half a century and is expected to continue at least until 2020. In conjunction with this technological development, electronics has turned almost completely into semiconductor electronics. Semiconductor technology and microelectronic manufacturing methods, respectively, make it possible to simultaneously produce large numbers of similar devices and components with dimensions that are much too small for conventional technologies like precision mechanics.

Semiconductors entered the nano-technology era when structure dimensions went below 100 nm in the 2002–2003 timeframe, after the most leading semiconductor companies, like Intel, AMD, Infineon, Texas Instruments, IBM, and TSMC had introduced the 90 nm technology node. Here, technology node refers to the level of CMOS process technology defined by the International Technology Roadmap for Semiconductors (ITRS). In 2011, wafers with 22 nm technology came into production; its technology successor, the 16 nm technology, is expected to follow likely in 2013.

However, packaging in microelectronics cannot keep pace with this impressive development. Packaging is the final manufacturing process transforming semiconductor devices into functional products for the end user. It has to fulfill a wide variety of tasks regarding system functions, e.g. power supply, signal distribution, protection, and compatibility with regard to the system's application. Hence, packaging is a key enabling technology achieving the requirements for the reliable operation of electronic systems and for reducing the size and the cost at the system and product level. However, packaging is not only the enabling force but today also the limiting factor in the further development of electronics system integration.

Nano- and biotechniques promise to offer new approaches and solutions to close the growing gap between the development of CMOS technology and the improvements in packaging technology. The application of nanotechnology, i.e. the manipulation and control of matter on the nano-scale, in packaging makes use of size- and structure-dependent properties and phenomena distinct from those of bulk materials. Nano-materials exhibit a much larger specific surface or interface area than coarser materials which leads to a totally different surface-volume ratio. Furthermore, the confinement of atoms and electrons within boundaries of a few nanometers lead to particular nano-scale properties. By this, nano-techniques enable novel approaches and solutions for example regarding nano-sized interconnects, sensor and information processing functionalities, nano-power sources, heat removal, and the protection and functionalization of surfaces matching the system to the environment.

Bio-objects like DNAs or proteins with their corresponding dimensions on the nm- to μm-scale and their particular properties for bio-sensing can be applied in packaging very similar to nano-technology. Bio-techniques offer very particular functionalities like self-organisation, self-assembly, programmability and biocompatibility so far not utilized in packaging. Further into the future, such bottom-up approaches are expected to open many unique solutions for nanoelectronics that would not be possible with top-down methods based on photolithography. Nanomaterials with their superior properties and bio-techniques with their opportunity for self-assembly and self-repair had fired up the imagination of engineers and scientists alike. This was the reason that in 2003 colleagues from our Electrical and Computer Engineering Department, the Mechanical Engineering Department, the Sciences Department (Physics, Chemistry and Biology) and the Medical Department came to the idea to establish a Research Training Group "Nano- and Biotechniques for Electronic Device Packaging" at our Technische Universitt Dresden, Germany. This idea came finally to life in the fall of 1995 when the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) agreed to provide funding for 20 PhD and 2 postdoc positions over a period of nine years. Since then professors, PhD students and many other scientists of TU Dresden have been contributing in an astonishing way to this most recent field in packaging.

Nano- and bio-techniques are still in the early stages of research and development. Nevertheless, some of the results, like biosensors on silicon nanowires, are tempting to being transferred to industrial applications of packaging. Therefore, the intentions of this book are to provide an overview about what is possible in packaging with these new technologies and where are the limitations. The book is composed as a compendium of in-depth reviews. It covers the broad aspects of the field from the present and future of packaging (Part I) via modeling and simulation of three-dimensional electronic systems (Part II) and packaging-related material and technology issues (Parts III and IV) up to the point of functionalized surfaces (Parts V and VI). Each of these six parts of the book will be introduced by a chapter providing a more comprehensive overview. Most of the other chapters include more a focus on the authors' own research in each respective field. Nevertheless, each chapter presents an outlook about what can be expected in the future and provides an extensive reference listing. We hope that this will give the reader a resource for keeping pace with the fast development in this emerging field. It is hoped that he can find stimulating new ideas and some food for thought.

The book is the result of the commitment of the many co-authors most of them associated with our Research Training Group. It was impressing to observe their verve and enthusiasm to make this book a reality. The editors would like to express their thankfulness to Martin Waegner who provided the necessary support to bring the chapters into the right shape and to manage the electronic files. We would also like to express our appreciation to Springer Verlag for the opportunity to publish this book and, in particular, to Thomas Lehnert and Ulrike Butz for their excellent cooperation, but also for their patience when repeatedly faced with delays due to the authors' workload.

Dresden
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Part I
Future of Packaging

Chapter 1
Packaging for Electronic Systems

Gerald Gerlach

1.1 Introduction

Electronic systems are systems comprising electronic devices, circuits and components which are designed to accomplish certain complex functions. Examples are cell phones, computers, electronic music systems like MP3 players, anti-lock braking systems (ABS), quartz watches, implantable cardiac pacemakers, and many others. Usually, electronic systems do not contain only electronic components like integrated circuits but also mechanical, optical and other ones providing functionalities far beyond of pure electronic devices. An often used term for such miniaturised systems is micro- or nano-opto-electro-mechanical systems (NOEMS, MOEMS or simply nano- or microsystems). To accomplish the complex functions of such systems packaging has to integrate the function components into a working system, has to maintain these system functions independently of ambient and operating conditions, and has to couple the system to its environment, e.g. the operator or costumer of the system.

Hence, packaging is a system technology and it has to fulfil a wide variety of tasks regarding system functions, e.g. power supply, signal distribution and processing, protection, and compatibility with regard to the system's application. Estimates state that only one third of total costs refers to the production of the silicon chips within electronic systems, whereas one third is assigned to packaging and testing, each [47].

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1.2 From Electronic Devices to Electronic Systems

1.2.1 Electronic Devices and Components

Electronic devices are physical entities used to affect any charge carriers (electrons in metals, electrons and holes in semiconductors, electrons or ions in dielectrics, ions in ion conductors) or their associated fields to evoke intended functions of the electronic system. Some common electronic devices are resistors, capacitors, coils, diodes or transistors. Usually, components are often categorized as

- passive components: devices that consume (but do not produce) energy or that are incapable of power gain, respectively, e.g. resistors and capacitors, or as
- active components, e.g. transistors and thyristors.

A radical change in the entire field of electronics began when in 1947 the transistor was invented [2, 57, 58] and when in 1958 the first integrated semiconductor circuit was built [23]. Ever since, electronics has turned almost completely into semiconductor electronics. Semiconductor technology and microelectronic manufacturing methods, respectively, make it possible to simultaneously produce large numbers of similar devices and components with dimensions that are much too small for precision mechanics.

Components are generally intended to be connected together to provide a particular function, usually by being soldered to a printed circuit board (PCB) or as an integrated circuit. Examples for such particular functions are amplifiers, rectifiers, radio receivers, oscillators for analog sub-systems and logic gates, counters, multiplexers, microprocessors and memory devices for digital sub-systems.

The integration of large numbers of single transistors into a small semiconductor chip has many advantages over manually assembled circuits based on electronic components:

- mass production capability,
- highly increased reliability,
- building-block approach for effective design of circuits and complex systems,
- performance improvement, and
- most important, cost.

The cost and performance advantages of ICs over discrete circuits are caused by the following reasons:

- The electronic devices of multiple ICs are fabricated in parallel on a silicon wafer using photolithography to transfer the pattern of the device structures from photomasks to the wafer surface and are not constructed as one transistor at a time.
- ICs dies require much less space and, hence, much less material to construct a circuit than as a discretely assembled circuit.
- Performance of integrated ICs is much higher since their much smaller components are located closely side by side and, hence, switch much quicker and consume much less power.

Table 1.1 Integrated circuits

Analog ICs	• Work by processing continuous signals, • Perform functions like amplification, active filtering, demodulation, mixing, etc., • Examples: transistor amplifiers, operational amplifiers, oscillators, power management circuits, sensors.
Digital ICs	• Contain logic gates, flip-flops, multiplexers, and other digital circuits, • Use binary mathematics to process "one" and "zero" signals. • Examples: microprocessors, microcontrollers, application-specific integrated circuits (ASIC), digital signal processor (DSP), field-programmable gate arrays (FPGA), computer data storages (memories).
Mixed-signal ICs	• Combine analog and digital circuits on a single chip to create functions such as analog-to-digital (ADC) and digital-to-analog converters (DAC), • Offer smaller size and lower cost, but must carefully account for signal interference, • Examples: delta-sigma modulators, digital radio chips, digitally controlled sound chips, cellular telephones, software radio, LAN and WAN router

In general, integrated circuits can be classified into analog, digital and mixed signal (both analog and digital on the same chip).

Semiconductor devices and integrated circuits, i.e. microelectronics, have been responsible for the tremendous growth of electronics industry during the last decades. Since then electronics has become the largest industry, surpassing agriculture, auto, and heavy metal industries, being the industry of choice for a country to prosper [64, vol. 1, p. V] Table 1.1.

1.2.2 Microsystems

The discovery of the piezoresistive effect in 1953 made it possible to apply semiconductor materials and microelectronic production methods not only to electron devices but also to non-electronic components [59]. The first description of how to use a locally thinned silicon membrane with integrated piezoresistors as mechano-electrical transducer dates back to 1962.

Since then, uncountable, new miniaturised function and form elements and components have been introduced, combining electrical with other non-electrical functions and using semiconductor technology as well as especially developed microtechnologies. Examples for microsystems with highest market volume are inkjet print heads, pressure and acceleration sensors, silicon microphones, microfluidic chemical analyzers, and RF microsystems.

In general, microsystems constitute integrated, miniaturised systems that

- comprise electrical, mechanical and even other (e.g. optical, fluidic, chemical, biological) components,
- are produced by means of semiconductor and MEMS technology, respectively,
- contain sensors, actuators and signal processing functions,
- comprise function elements and components in the range of micro- and nanometres and has itself dimensions in the range of micro- or millimetres.

The term "microsystem" describes this kind of electronic system in a more generic way because not all microsystems comprise the complete set of non-electric components like the abbreviations MOEMS and NOEMS pretend. Microsystems can be characterized by the semantics of its word components "micro" and "system" (Table 1.2):

- Components or elements of microsystems have a typical size in the sub-millimeter range and these sizes are determined by the components' or elements' functions. In general, the size lies in the range between micrometers and nanometers (Fig. 1.1). Such small structural sizes can be achieved by directly using or adapting manufacturing methods of semiconductor technology.
- Recently, nanotechnology is gaining massive public attention. The prefix "nano" is used there in two respects. On the one hand, nanotechnology can be applied for down-scaling micrometer-sized dimensions, such as the thickness of function layers, to the nanometer range. Typical gate thickness in microelectronic CMOS-transistors is today only a few nanometers. Here, the term nanotechnology (nanoelectronics, nanoelectronic components) is used for extremely miniaturised devices where the basic physical laws and design procedures still apply. On the other hand, the term nanotechnology is used for devices, which are only possible at a certain smallness. Examples are quantum effect elements (e.g. quantum dots and quantum wires) or single-electron devices.
- Microsystems consist of several components that, in turn, consist of function and form elements (Fig. 1.2). The components have specific functions, e.g. sensor, actuator, transmission, memory or signal processing functions and they can be constructively autonomous entities (e.g. an integrated circuit). Microsystems include both non-electric and (micro-) electronic as well as electrical components. The system character is due to that the system can only fulfil the total function if the components interact as a complex miniaturized unity.

Figure 1.3 shows the typical setup of a microsystem. Sensors and actuators as well as signal processing components are connected together but also with the microsystem's environment, e.g. with an entity or a technical process that has to be controlled. The individual components consist each of a number of function and form elements that can be produced using corresponding materials and applying micro- and system technology. Packaging relates to the connection between the microcomponents as well as generally between the microsystem and the environment. This includes

Table 1.2 Aspects of microsystem technology

Microsystem technology			
Micro- and nano-technologies		System technologies	
Functional	Technological	Functional	Technological
• Microelectronics,	• Semiconductor technology,	• System theory,	• Integration techniques, assembly,
• Micromechanics,	• Thin-film technology,	• Signal theory,	• Wiring techniques,
• Microoptics,	• Patterning, lithography techniques,	• Design methodology,	
• Microfluidics,	• Micromolding,	• Test and diagnostics,	• Bonding techniques
• Microchemistry,	• Imprinting	• Quality assurance	
• Cell biology			

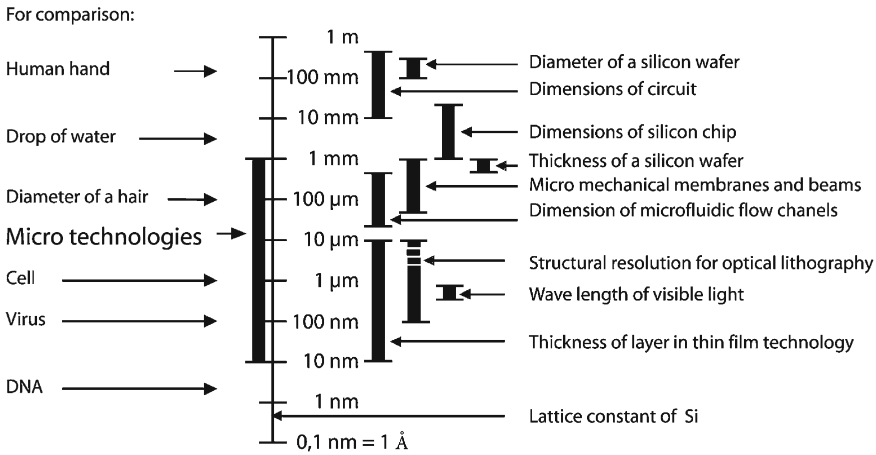


Fig. 1.1 Dimensions in micro- and nanotechnology

power supply, signal transfer and processing, supply of sensor quantities, connecting actuator components with the corresponding sites in the surroundings, as well as the protection of the microsystem and its compatibility to the environmental conditions.

1.2.3 Microelectronics and Microsystem Technology

The emergence of microsystem technology is the immediate response of the two major drawbacks of microelectronics:

- Microelectronics is limited to electronic devices and the integration of electronic functions. Because pure electronic systems are not able to process non-electrical

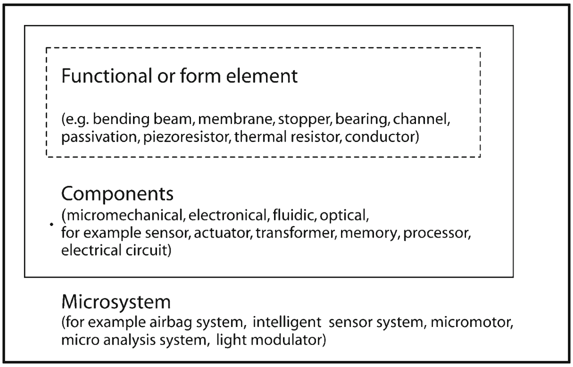


Fig. 1.2 Terminological hierarchy in microsystem technology

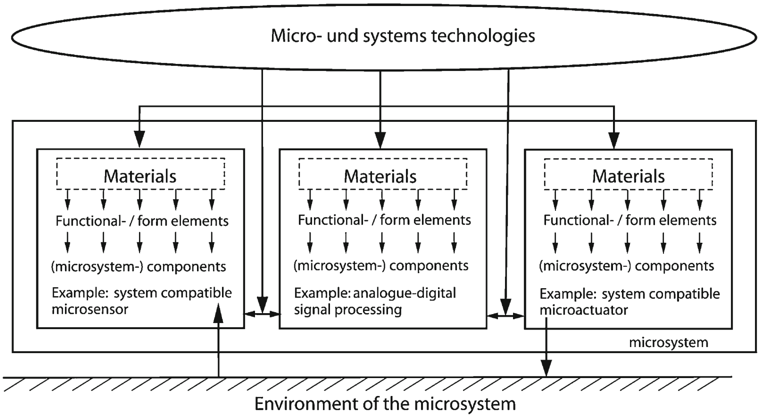


Fig. 1.3 Structure and integration of microsystems

values more generic systems should also comprise sensor functions to read signals from the system environment and actuators to affect the environment. In the past this required a combination of microelectronic components and classical components produced by precision mechanics. However, this reduced the miniaturising potential and the level of integration that could be reached. As a result, reliability decreased.

- The manufacturing process of semiconductor technology allows the fabrication of two-dimensional, but not of three-dimensional structures. However, a number of functions—especially non-electrical ones—require three-dimensional function components and their three-dimensional integration

As a result, microsystems technology is the logic continuation of microelectronics technology. In the same way, there are several reasons for the close connection of the development of microsystem technology with microelectronics:

- Within the microtechnologies such as micromechanics, microfluidics, microoptics etc., microelectronics has still an outstanding position: Given the current state of

Table 1.3 Comparison of typical characteristics of microelectronics and microsystem technology

Criterion	Microelectronics	Microsystem technology
Components	Standardized (e.g. memories, processors)	Heterogeneous
Production numbers	$10^5 \ldots 10^8$	$10^2 \ldots 10^6$
Applications	Electronic	Electronic, mechanical, fluidic, optical, chemical, biological, ...
Structural dimension	Two-dimensional	Three-dimensional
Design	Automated	Heterogeneous with limited design support

the art, microsystems without microelectronic components for processing analog or digital signals appear not to be meaningful.

- Only semiconductor and thin-film technology provide manufacturing processes that are able to efficiently produce structures in the range of micro- and nanometers in high numbers. Additionally, microelectronic manufacturing processes show the advantages of parallel processing of identical elements or components within a single process step as well the use of completely new physical-chemical procedures well-suited to miniaturization.
- Both microsystem technology and microelectronics are dominated by silicon which has excellent characteristics in comparison with compound semiconductors, for instance. Silicon can be produced with the highest chemical purity and crystal perfection a large number of technological procedures and sensoric as well as actuating effects rely on.

Table 1.3 compares typical characteristics of microelectronics and microsystem technology. Microelectronics is characterized by large production numbers and a high standardisation of components. The adjustment to the particular is then reached by the programming options of microprocessors and microcomputers as well as by memory circuits. Due to the diversity and heterogeneity of microsystem technology, it will not be possible to find similarly standardised applications with similarly high production numbers. The only option here is to use and to adapt the high-developed fabrication methods of semi-conductor technology, respectively.

1.3 Packaging

1.3.1 Definition

General electronic systems or microsystems are systems which are designed to accomplish certain complex functions. They comprise electronic as well as mechanical, optical, fluidic, chemical, biological and other circuits and components. To accom-

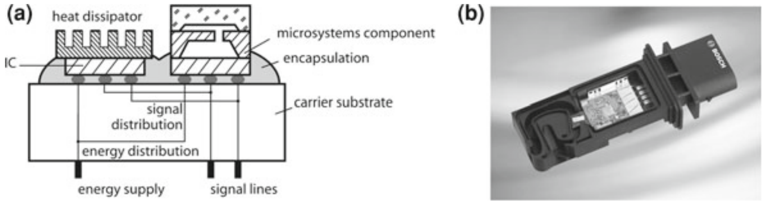


Fig. 1.4 Microsystem packaging with complex (mechanical, electrical, sensoric, thermal and protection) functions, **a** principal structure (according to [63]; **b** example air mass flow meter (Robert Bosch GmbH) (from [15])

plish the complex functions of such systems packaging has to integrate the function components into a working system, has to maintain these system functions independent of ambient and operating conditions, and has to couple the system to its environment, e.g. the operator or costumer of the system. In general, packaging serves two functions [24]:

- It protects the devices from the environment.
- It protects the environment from the device operation.

Hence, packaging is a system technology and it has to fulfil a wide variety of tasks regarding system functions, e.g. power supply, signal distribution, protection, and compatibility with regard to the system's application.

Packaging can be defined in the following:

Definition 1 Packaging is the technology that bridges the gap between miniaturized electronic and non-electrical function elements and components as well as to the environment to constitute systems with particular complex functions, that match the system to the environment given by the intended application and that secures and maintains the system's properties during entire life-time.

Hence, packaging is a key enabling technology achieving the requirements for the reliable operation of electronic systems and for reducing the size and the cost at the system and product level. It is of multidisciplinary nature comprising various fields ranging from materials and technology (including assembly) via modelling and simulation to application-determined aspects.

1.3.2 Requirements for Packaging

Packaging has to carry out a wide variation of tasks which result from the required system functions (Table 1.4, Fig. 1.4) as well as from product requirements for the different fields of application (Table 1.5).

Table 1.4 Functions of packaging

Level	Functions
Mechanical	Structural framework for function and form elements in the system, stress relief;
Electrical	Power supply and distribution, signal distribution;
Sensoric	Signal sensing, sensor functionalization;
Thermal	Heat dissipation management;
Protection	Protection of all sub-components and the total system against disturbances affecting the system's functions (e.g. mechanical, optical, chemical, electromagnetic);
Functionalization	Adjustment of system's surface properties to interface requirements (e.g. optical, biomedical);
Compatibility	Matching the system's surface to the environment: bio-compatibility, optically (e.g. refractive index), mechanically (e.g. with respect to friction), media compatibility, adhesion.

Table 1.5 Typical requirements regarding products in different market segments[a]

Area	Temperature range in °C	Mechanical impact load	Relative humidity in % r.H.
User	$0 \ldots +60$	Drop test (1 m on concrete)	normal
Industry	$-20 \ldots +80$	$\leq 5\,g$	85 (at 85°C)
Automotive (engine-related)	$-40 \ldots +180$	$\leq 3\,g$	85 (at >100°C)
Aviation and aeronautics	$-55 \ldots +125$	$\leq 1500\,g$	85 (at 85°C)
Information and communictaion	$-40 \ldots +85$	Drop test (1 m on concrete)	85 (at 85°C)
Medical	$-20 \ldots +80$	$\leq 5\,g$	Normal

[a] g acceleration of gravity

In order to carry out such a variety of tasks, microsystems as well as electronic systems are built hierarchically with each level being assigned to different functions [34]. In packaging, four levels are distinguished in general:

1. Chip level: Packaging on the chip, e.g. gate-to-gate interconnections on a monolithic silicon chip; passivating layers on the chip surface, on the individual chip or still on the entire wafer,
2. Module level: Chip assembly, e.g. bonding chip to substrate; packaging of an integrated circuit,
3. Board level: Assembly of modules, e.g. printed circuit boards with sensors, ICs and discrete components,
4. System level: System assembly, e.g. motherboard, backplane.

Other authors prefer a three-level hierarchy [19]:

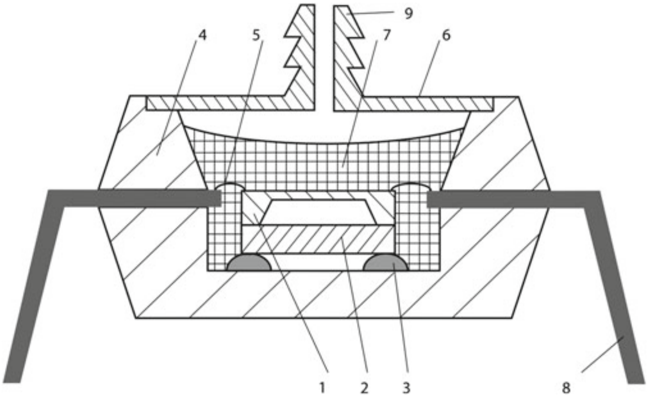


Fig. 1.5 Assembled pressure sensor chip: *1* sensor chip, *2* glass counter-body, *3* gluing points for chip fixing, *4* IC housing, *5* metal wire bridges, *6* cover, *7* protection gel, *8* electrical connections (lead frame), *9* measuring pressure inlet

1. Die level,
2. Device level,
3. System level.

Each level uses particular techniques. For instance, the deposition of passivation layers applies thin-film technology, whereas assembling MEMS chips on the carrier substrate uses the particular bonding techniques. Module assembly often uses soldering and gluing, based on thin- or thick-film technology, respectively.

Figure 1.5 shows the typical assembly of a piezoresistive pressure sensor with a common DIL (Dual in Line-) package. The core element of the sensor is a piezoresistive silicon pressure sensor chip. The measured pressure is lead to the sensor via the specific pressure inlet. Since the measured signal should only be affected by the pressure to be measured and not by thermal or mechanical deformations, the sensor chip is bonded to a glass counter-body with a respective temperature coefficient of expansion (mostly silicon or glass) and soft-glued into the housing. This avoids unwanted deformations of the sensor chip and, hence, of membrane and piezoresistive resistors within the membrane, respectively.

The electrical contacting of the piezoresistors in the silicon chip to the exterior electrical connections is carried out via wire bridges, usually by Au or Al wires.

Many applications of such pressure sensors are connected with harsh environment, thus negatively affecting the semiconductor surface (e.g. by corrosion). Therefore, the sensor chip is embedded into a protection gel which shows a low Young's modulus, i.e. is very soft. This ensures that the pressure loss of the measuring pressure by the protection gel on its way to the silicon bending plate is negligible.

The set of requirements of Table 1.6 illustrates clearly that the demands in packaging exceed those in electronics and microelectronics by far. This is caused by the following reasons [26, 40]:

Table 1.6 Requirements for packaging (cp. Fig. 1.5)

Domain	Requirements
General	• Low costs • Small size • High reliability and quality
Electrical *On-chip metallization*	• Good adhesion, preventing delaminations • Alignment precision • No scratches, interruptions, and short-circuits • Small contact resistance • Good edge coating
Wire bridges	• Strength • Adhesion • Positioning accuracy • Prevention or suppression of voids formed at the boundary interface in alloy to metal bonding (Kirkendall voids) • Geometry (height, curvature)
Lead frame	• Strength • Adhesion • Solderability • Contaminations • Corrosion
Mechanical	• Height, dimensions, precise orientation • Mechanical defects • Shock and vibration resistance • Intrinsic stresses, deformations • Crack formation
Thermal	• Efficient heat dissipation • Resistance to thermal load changing
Protection	• Against humidity, moisture, corrosive environment • Quality and uniformity of passivations • No influence of light on piezoresistors (to avoid photocurrent at p-n junctions)
Functionalization	• E.g. non-stick coating
Compatibility	• Electromagnetic compatibility (EMC) • Biocompatibility (in case of biomedical applications) [25]
Impact on function parameters	• Long-term stability of function parameters (characteristic) • Low cross-sensitivity to disturbance variables

- In contrast to pure electronic devices, MOEMS devices need not only electrical power supply and other electrical signals but also non-electrical (mechanical, optical, fluidic) signals and quantities.
- Each of these components requires a different set of requirements for packaging, optical alignment, thermal management, mechanical support, and handling.
- Selective influence of physical quantities and chemical species on the sensors: The sensor has to be protected e.g. against electro-magnetic radiation, temperature and

Table 1.7 Failure mechanisms in electronic devices and MOEMS

Material-interaction-induced mechanisms	• OHMic contact degradation • Surface state effects • Package molding contamination whith impurities in packaging compounds causing electrical failure • Delamination
Electrically induced failure mechanisms	• Electromagnetic interference damage • Electrical stress due to electrostatic discharge at high electromagnetic fields • Electromigration causing electrically induced movement of material in the chip • Short-circuits due to hillock and whisker formation • Burnout—localized overstress • Overcurrent
Mechanically induced failure mechanisms	• Large elastic deformation • Plastic deformation • Die fracture due to mismatch of thermal expansion coefficients • Brittle fracture • Die-attach voids • Wear • Solder joint failure by creep fatigue or intermetallic cracks
Chemically induced failure mechanisms	• Corrosion • Diffusion of media (e.g. ions, humidity) • Ionic contamination • Depolymerization
Environmentally induced failure mechanisms	• Humidity effects due to moisture absorption by the package

humidity, whereas other quantities are expected to affect the system, at least locally (e.g. measuring quantities in sensors, chemical species in lab-on-chip systems). This requires selective protection measures of functional areas.
- The small dimensions of micro- and nanosystems themselves cause failure mechanisms, some of them not yet entirely studied.

1.3.3 Failure Mechanisms in Packaging

Basically, fundamental failure mechanisms occur directly at the MOEMS element (e.g. pressure sensor chip), i.e. at the lowest level of packaging. Appropriate packaging measures have to avoid, to decelerate or to delay these mechanisms. Due to operating conditions, failures can be caused by many sources of overstress and wearout [45] (Table 1.7).

Table 1.8 Design for reliability

Level	Failure mechanisms	Measures
1. + 2. Chip packaging	Corrosion	Sealing and encapsulation
	Fracture	Reduction of mechanical stresses, avoiding defects
	Electromigration	Application of materials with higher conductivity; reduction of current density
3. Packaging of function groups	Crack formation	Load decrease; application of high-temperature materials; matching coefficients of thermal expansion of materials; reduction of temperature gradients in the package
	Fatigue fracture	Reduction of mechanical stress load; limitation of temperature range; application of other materials; changing geometries and dimensions
	Delamination	Improved adhesion; reduction of film stresses; limitation of temperature range
	Interdiffusion	Reduction of temperature
	Radiation damages	Screening
4. System packaging	Corrosion	Avoiding and reducing defects; reduced humidity range; barrier layers; reduced temperature
	Abrasion, wear	Reduced friction

Packaging is often the least developed aspect of technology in electronic systems and MOEMS and often give rise to the main causes of long-term component and, hence, system failure [50]. In order to comply with the main tasks of packaging, the structure of electronic systems and of microsystems have to ensure that operation conditions do not have an interfering effect on the characteristic or does not damage the system, at least over a specific operating period. This requires a specific design for the packaging—the so-called Design for Reliability. Therefore, system design has always to be combined closely with packaging design.

1.4 Functions of Packaging

Table 1.4 has provided an overview of the diverse functions that packaging has to fulfill. In the following, selected functions will be considered closer. Interested readers are referred to [63] and [47] (especially regarding microsystems) as well as to [64] and [51] (for electronic components).

Table 1.9 Substrate materials for electronic systems

Substrate	Properties and characteristics
Silicon	• Hard and brittle • Bonding of Si dies with Si or glass applying gluing, glass soldering, eutectic bonding, anodic bonding or silicon direct bonding • Hermetically sealed contacts are possible • Metallization on Si for wire bonding
Ceramics	• Hard and brittle • Also used for electric wiring • Ceramic packaging often as two-piece set-up (carrier, cap) • Electrical interconnects can be made using thin- and thick-film techniques
Printed circuit board material	• Consists of carrier (glass-reinforced laminate) and binder (epoxy resin) • Flexible circuit boards based on plastic foil (PE, PI, PTFE) available
Plastics	• Moulding to coat function components that are electrically contacted to a lead frame • Function components are subjected to the harsh conditions of injection moulding • Hard to seal it hermetically due to high permeation
Metal	• Robust, easy to process • Can be hermetically sealed and used in harsh environments (stainless steel) • Suitable for smaller batch sizes

1.4.1 Structural Framework

One task of packaging is to geometrically arrange and fix the function components of electronic systems. For this, usually a carrier or a substrate is used. This is itself part of the housing.

a. Substrate Materials

Main materials for the geometrical carrier are the silicon chip itself (for monolithic integration), printed circuit board material, ceramics, plastics or metals (Table 1.9).

b. Thermal Matching

When assembling microsystems, often materials with different coefficients of thermal expansion have to be combined (see Table 1.9). The strain as difference in thermal expansion

$$\Delta\varepsilon = (\alpha_1 - \alpha_2)\Delta T \tag{1.1}$$

after heating or cooling causes a deformation of the compound system. Here, α_1 and α_2 are the expansion coefficients of the compound partners and ΔT the temperature difference to the bonding temperature. In practice, two ways are used to prevent the occurrence of mechanical stresses and deformations, respectively, in function and form elements of the electronic system:

- Usage of materials with matched coefficients of thermal expansion (e.g. silicon-glass bonded by anodic bonding; silicon-silicon)
- Mechanical stress decoupling through a highly elastic intermediate layer (e.g. soft glue above glass temperature).

1.4.2 Electrical Connections

Packaging for electronic systems has the task to supply function components with power and to contact them to each other and with the system environment via electrical signal lines and contacts.

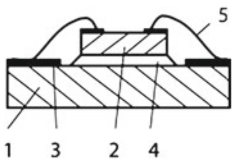
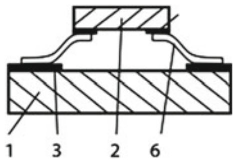
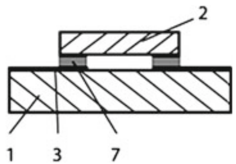
Table 1.10 shows the most-widely used techniques for electrically contacting silicon chips on substrates.

Wire bonding (Chip & Wire) is currently still the most widely used technique for contacting semiconductor chips. It uses micro wires with a typical diameter of $(20 \ldots 25)\,\mu\text{m}$, which form wire bridges. The energy required for the bonding is provided by ultrasound (ultrasound or US bonding), by a combination of heat and pressure (thermocompression or TC bonding) or heat, pressure and ultrasound (thermosonic or TS bonding). Al or AlSi1 wires are suitable for US bonding, Au wires for TC and TS bonding. A disadvantage is that fabrication of the wire bridges is done serially one after the other and not simultaneously.

For Tape Automated Bonding (TAB), soldering or TC bonding is used to contact the silicon die with a flexible lead frame. Here, contacting is performed simultaneously during one manufacturing step. A disadvantage is the comparatively large space required.

Flip-chip (FC) bonding [30, 31] also allows carrying out all contacting during one single manufacturing step. Compared to TAB, it requires less substrate area, though, enabling high packaging densities. Soldering bumps are deposited on the chips of a wafer array and after flipping the chips, these can be contacted with the interconnects on the substrate. A variety of contact systems (metals, alloys) as well as conducting polymers can be used as bumps. Temperature changes in combination with the resulting expansion differences between chip and substrate can lead to large shear deformations in the bumps. Usually, the entire gap between chip and substrate is filled with a so-called underfiller to reduce shear stresses by increased effective cross-sectional areas. In addition, it also provides better protection of the contacts from humidity and other chemical species.

Table 1.10 Techniques for electrically contacting bare chips on substrates

Technique	C & W Chip and Wire Bonding	TAB Tape Automated Bonding	FC Flip Chip Bonding
Schematic diagram			
Bonding process	Serial	Parallel	Parallel
Electrical connection chip-substrate	Wire bridges	Flexible lead frame	Solder bumps
Contacting	TS or US wire bonding	Soldering or TC bonding	Soldering, gluing or TC bonding

1 substrate, 2 Si chip, 3 bond pad, 4 glue, 5 wire bridge, 6 flexible lead frame, 7 solder bump

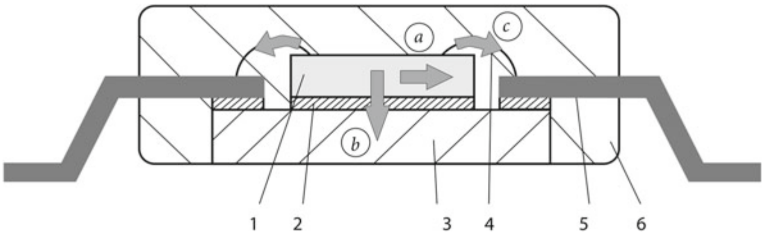


Fig. 1.6 Heat conducting paths from heat sources in electronic systems: **a** laterally within the die; **b** towards the heat sink; **c** via bonding wires and metal contacts *1* Si die, *2* bonding layer, *3* heat sink (copper), *4* bonding wires, *5* contacts, *6* housing

1.4.3 Heat Dissipation

Microsystem technology mainly uses heat sinks for dissipating heat. In microfluidics also convection can be used. Heat conduction takes place via (Fig. 1.6) [54].

- the silicon chip itself,
- separate heat sinks (mainly made of copper),
- electrical contacts (bond wires, lead frames, bumps, soldering joints).

Heat dissipation via plastic housings and embedding, circuit boards or ceramic substrates is poor due to their limited thermal conductivity.

1.4.4 Protection

Coating, encapsulation and sealing provide protection for sub-components and the entire microsystem against environmental disturbances that affect their functions. This refers to chemical influences like

- humidity,
- corrosive media (e.g. in process control),
- environmental contaminations (ionic contaminations such as sodium, potassium and chlorine ions caused by biogene (e.g. sweat) or non-biogene (e.g. salt water) sources),
- atmospheric gas components (e.g. NO_X and SO_2 in air and emissions)

and to mechanical damages.

a. Coating

The simplest form of protection against media impact is the coating of microsystem components or of the entire microsystem. The film will form a barrier to the corresponding chemical species. Passivation layers can be applied for die passivation and die isolation [19] and can already be deposited at wafer level prior to wafer dicing. In silicon micromachining, double layers of silicon dioxide (thermal SiO_2 as quasi-perfect defect-free layer) and silicon nitride (chemically almost inert) are particularly suitable [41]. On chip level, it can be differentiated between primary passivation (prior metallization) and secondary passivation (protection including metallization). Also organic materials are used for coating, such as silicone and fluor silicone gels (deposited with a thickness of up to millimeters), parylene (conform deposition during CVD process) and polyimide [47].

b. Separation Membranes

Pressure sensors often use stainless steel separation membranes for decoupling measuring pressure medium and silicon sensor chip. The stiffness of the separation membrane has to be as small as possible so that its flexibility remains negligible in comparison with the silicon bending plate. Therefore, corrugated membranes are used which show a very low stiffness. Pressure transfer is carried out via an oil-filled hollow space, where the oil filling has to be free of air or gas bubbles. In comparison to coating, separating membranes are much more resistant to chemical impacts. Their disadvantages are packaging costs, the required structure size and the limited operating temperature range.

c. Encapsulation

Microsystems can be encapsulated using [10, 63]

- sealing,
- injection moulding,
- application as liquids and hardening.

Typical materials are

- epoxy resins: These are the most common materials. They polymerize fast and without formation of volatile components. Amines, anhydrides or phenols are used as hardeners.
- cyanate ester: They have a higher glass temperature $(190\ldots290)^\circ$C and lower water absorption than epoxy resins.
- urethanes: They show excellent adhesive properties and an outstanding film conformity.

d. Hermetic Sealing

Hermetic sealing prevents the diffusion of humidity and water und thus increase long-term stability of the parameters of electronic components and microsystems.