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Preface

Nanotechnology enabled sensors is an exciting field to enter into. It is our intention to provide the readers with a deep understanding of the concepts of nanotechnology enabled sensors, handing them the information necessary to develop such sensors, covering all aspects including fundamental theories, fabrication, functionalization, characterization and the real world applications, enabling them to pursue their research and development requirements.

This book can be utilized as a text for researchers as well as graduate students who are either entering these fields for the first time, or those already conducting research in these areas but are willing to extend their knowledge in the field of nanotechnology enabled sensors. This book is written in a manner that final year and graduate university students in the fields of chemistry, physics, electronics, biology, biotechnology, mechanics and bioengineering, can easily comprehend.

Nanotechnology enabled sensors is multidisciplinary by nature. It is important that the readers are armed with the necessary knowledge of physics, chemistry and biology related to these sensors and associated nanosciences. This book does not assume that its readers are experts in the multidisciplinary world; however, a basic understanding of university level chemistry and physics is helpful.

In this book, the authors present sensors that utilize nanotechnology enabled materials and phenomena. The terminology and concepts associated with sensors are presented which include some of the relevant physical and chemical phenomena applied in the sensor signal transduction system. The role of nanomaterials in such phenomena is also detailed. Throughtout this book, numerous strategies for the fabrication and characterization of nanomaterials and nanostructures, which are employed in sensing applications, are provided and the current approaches for nanotechnology enabled sensing are described. Sensors based on organic and inorganic materials are presented and some detailed examples of nanotechnology enabled sensors are explained.

Acknowledgments

We have been fortunate that many people supported and assisted us during the writing of this book.

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Contents

Chapter 1: Introduction

1.1 Nanotechnology

The term *nano* in the SI units means 10^{-9}, or in other words, one billionth. It is derived from the Greek word for dwarf. Materials, structures and devices that have dimensions lying in the nano scale range are encompassed within *nanosciences*. Materials that have at least one dimension less than 100 nm may be considered to be nanodimensional (**Fig. 1.1**).

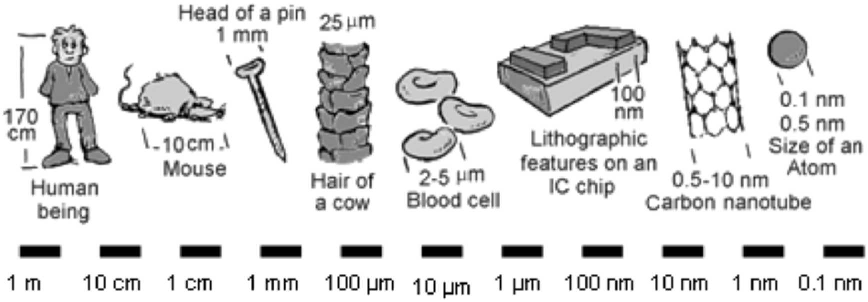


Fig. 1.1 Examples of objects with different dimensions (by Kourosh Kalantar-zadeh).

Nanotechnology comprises technological developments on the nanometer scale. The *United States' National Nanotechnology Initiative* website (http://www.nano.gov) defines nanotechnology as: "The understanding and control of matter at dimensions of roughly 1 to 100 nm, where unique phenomena enable novel applications."

In the nano range, the physical, chemical, and biological properties of materials are unique. Therefore, nanotechnology provides us with tools to create functional and intelligent materials, devices, and systems by controlling materials in the nano scale, making use of their novel phenomena and associated properties.

Nobel laureate Richard Feynman provided one of the defining moments in nanotechnology when in December 1959 he conducted his visionary lecture entitled “There is Plenty of Room at the Bottom” not just “There is Room at the Bottom”.[1] In his lecture, Feynman said: “What I want to talk about is the problem of manipulating and controlling things in a small scale … what I have demonstrated is that there is room - that you can decrease the size of things in a practical way. I now want to show that there is plenty of room. I will not now discuss how we are going to do it, but only what is possible in principle … we are not doing it simply because we haven’t yet gotten around to it … arrange the atoms one by one the way we want”. What Feynman realized was that “at the atomic level, we have new kinds of forces, new kinds of possibilities, and new kinds of effects. The problems of manufacture and reproduction of materials will be quite different”.

Nanotechnology is multidisciplinary in its nature. It not only concerns physics and engineering, it encompasses many other disciplines, in particular chemistry and biology. Consequently, it is essential that people taking an active role in nanotechnology must embrace the disciplines of science, engineering, and even philosophy.

Varied approaches have emerged for the development of nanomaterials, nanostructures and nanodevices. They are generally categorized as *top-down* and *bottom-up* approaches. Top-down approaches are those by which the bulk dimensions of a material are reduced until nanometer size features are produced. A well-known example of the top-down approach is the reduction in dimensions of the transistors on silicon chips which are fast approaching the nanoscale. By contrast, bottom-up approaches involve assembling structures molecule by molecule, or atom by atom, to fabricate structures with nano dimensions such as formation of self-assembled monolayers. Nanotechnology has become more tangible since bottom-up and top-down approaches started to coincide. Clearly, the successful realization of nanotechnology-enabled devices rests on the perfect amalgamation of these two approaches.

Moore’s law describes that computing power (in effect the number of transistors on a silicon chip) is doubling every 18 to 24 months. In fact silicon chips have followed this rule quite nicely for four decades. However, due to inherent material properties, no one expects that silicon based electronics can follow Moore’s law forever. Nowadays transistor technology features have reached dimension of 50 nm, yet transistors are still larger than the average size of most molecules. Continuing this trend, the silicon-based industry will become stagnant in or around 2015 when there will no longer be a possibility to shrink dimensions.[1]

The predictions are that organic and molecular based transistors will emerge and nanotechnology will play a pivotal role to ensure that Moore's law remains valid.[2,3] This will perhaps be one of the most clear cut examples of how bottom-up and top-down fabrication strategies are meeting in our time, and must be able to coexist and help each other in order to provide solutions for our needs.

We are fortunate to have at our disposal a myriad of scientific and technical tools and processes that are now well established. These include: high resolution characterization techniques, ion and molecular beam fabrication, nano-imprint lithography, atom by atom manipulation, a growing knowledge of cell biology, etc. The proliferation of these tools enable the measurement, fabrication, characterization and manipulation of nanostructures. New instruments with nanoscale resolution are accelerating scientific discovery, providing quality control in the fabrication of nanostructures, and stimulating novel approaches in miniaturization. These tools and processes, among with many others have helped us to delve into this area with greater confidence.

Despite having many tools at our disposal, we are only at the very beginning of our exploration into the nanotechnological realm. There are still many untouched areas in nanotechnology. Nanotechnology researchers with open mind and meticulous ability are required to make observations in all the disciplines available, to allow amalgamating ideas into new theories and developments. Nanotechnology researchers with strong knowledge in different disciplines must be willing to think beyond the realm of their initial training, as being merely an engineer or a scientist is no longer sufficient. An example comes from Albert Einstein (**Fig. 1.2**), who as part of his PhD program was able to calculate the size of a sugar molecule from the experimental data on the diffusion of sugar in water.[1]

Currently nanotechnology is in the forefront of technological discussions, debates and developments as scientists, policy makers and entrepreneurs endeavor to fully harness its capabilities and unleash a broad range of novel products.

It has been proven historically that the emergence and demise of economically powerful and industrial nations depend on their technological prowess. It is likely that countries that are playing a pioneering role in nanotechnology will reap the financial benefits and prosper altering our economical and social balances.

Fig. 1.2 Albert Einstein (Reprinted with permission from Javad Alizadeh – by Javad Alizadeh).

We are already beginning to experience some of the benefits that it has to offer. Nanotechnology enabled sunscreens are already enjoying commercial success and nano magnetic materials are available for the fabrication of highly dense data storage. Carbon nanotubes can be purchased cheaply. Nanoporous and nanostructured thin films have found numerous applications in the building industry and home appliance. Antimicrobial wound dressings, which use nanocrystalline silver to provide a steady dose of ionic silver to protect against secondary infections, are already in the market, as are cosmetics and skin protection products that fully utilize the capabilities of functional nanomaterials. Superior and cheaper products have been realized, and with their initial success, our expectations from nanotechnology are growing.

We are eagerly waiting to see changes for the better in our lives coming from nanotechnology. We have already witnessed the dramatic changes that our day-to-day lives have undergone in the last decades, owing to the emergence of home computers, internet, and mobile phones. As our palettes broaden and continue to grow, so too does our thirst for new products. In such cases, conventional technologies may fail to provide us with the advances that we so desperately crave. It is not beyond the realm of possibility that in the coming decades our lives may once again be revolutionized by products realized though the advances that nanotechnology can provide.

Nanostructures exist naturally in biological systems. Understanding these systems will allow us to improve the way we manage our health care and medical diagnostics. Clearly these days, bio-nanotechnology is among the first areas that is finding real world applications. Labeling and disease markers, drug discovery research, and diagnostic tests are among the pioneering developments.

Nanotechnology has the potential to have enormous impacts on manufacturing and construction industries. Smart nano materials may be employed to resolve the energy problems and provide advanced structures with desired capabilities.

Nanotechnology is in its infancy, and we have just taken the first step into it and consequently our knowledge in this area is still rudimentary. There are still major hurdles that must be surmounted. For example, interfacing between the nano-world and macro-world has not been established properly. Other than extremely expensive tools in the labs, reading tiny signals from the nanomaterials and sending the orders to them remain challenging tasks. There are still many ambiguities as we delve into the nanotechnological realm, as definitions and standards are still vague. What makes it more difficult is that nanotechnology has not been standardized yet. It consists of diverse materials, disciplines and techniques. It is becoming overtly difficult to come up with processes that can be adopted worldwide.

It is needless to say that among the multitude of possibilities that nanotechnology presents, there may be accompanying dangers. The possible negative effects of nanomaterials on our health and on our environmental are still relatively unclear. Our minds may wander on the verge of science fiction when we think about nanotechnology. In Drexler's "Engines of Creation",[4] the author depicted a visionary view of godlike control over materials by creating self-replicating assemblers which produce new creations. Bill Joy, a scientist at Sun Microsystem, drew inspiration from Drexler's book, predicting the possibility of self replicating nanomaterials called "grey goo" which could pose serious danger to the environment **(Fig. 1.3)**. It is with this type of thinking that scientists must act responsibly and tread cautiously when embarking on nanotechnology research. In a similar manner to chemicals such as dichloro-diphenyl-trichloroethane (DDT), which were the origins of terrible chemical pollution, scientist embarking on nanotechnology research should be vigilant to ensure that such disasters are not perpetuated once again. After all, Bill Joy's outlook of "grey goo" may not be so far fetched!

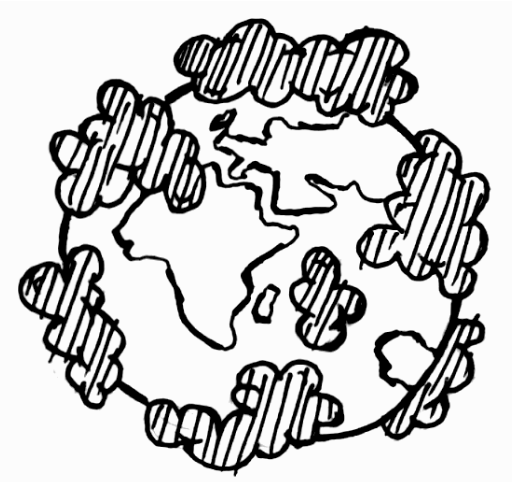


Fig. 1.3 Gray goo! (by Kourosh Kalantar-zadeh).

Despite these potential drawbacks and fears, there is much to look forward to in nanotechnology. With the nanotechnology market predicted to create revenues of over 1 trillion dollars per year by 2015,[5] there is great optimism. There is no doubt that nanotechnology has solid commercial prospects, however, it must be kept in mind that the task of converting basic discoveries into marketable products will be long and hard.[6]

1.2 Sensors

The word *sensor* is derived from the Latin word "sentire" which means to perceive.[7] A sensor is a device that responds to some *stimulus* by generating a functionally related output.[8] Exposure to a certain analyte or change in ambient conditions alters one or more of its properties (e.g. mass, electrical conductivity, capacitance, etc.) in a measurable manner, either directly or indirectly.

Quite simply our motivation for having sensors is so that we will be able monitor the environment around us, and use that information at a latter stage for another purpose. It is through sensors that we make our contact with the world.

A sensor should be sensitive to the *measurand* and insensitive to any other input quantity. It is essential that environmental effects such as temperature, humidity, shock and vibrations be accounted for. All these factors can have a negative impact on the sensors' performance. As a general rule, sensors should be inexpensive yet reliable and durable. They should provide accurate, stable, high resolution, low cost sensing. Each application places different requirements on the sensor and sensing system. However, regardless of the associated application all sensors have the same object: to achieve accurate and stable monitoring of the measurand.

In recent years, the development of sensors has become increasingly important. Sensor technology has flourished as the need for physical, chemical, and biological recognition systems and transducing platforms grow. Nowadays sensors are used in applications ranging from environmental monitoring, medical diagnostics and health care, in automotive and industrial manufacturing, as well as defense and security.[9] Sensors are finding a more prominent role in today's world, as we place strong emphasis on devices aimed at making our lives better, easier, and safer.

We may not even realize it, but sensors are found commonly around the household. They are in electrical devices from surge protectors to automatic light switches, refrigerators and climate control appliances, toasters, and of course in smoke and fire detectors. They are found most toys that have interactive capability. We also encounter sensors in everyday life: entering a department store with automatically opening doors, or in our automobiles, monitoring parameters such as the oil pressure, temperature, altitude and fuel levels. Sensors are installed in gas cook tops, where they determine whether or not the pilot is on, and if not, halt the gas flow preventing the room from being filled with gas. The function of voltage sensitive transistors is not so obvious to us, yet millions of them are contained within central processing units of computers, which are used to convert analogue signals into digital ones.

Many complex machines incorporate sensors. Aircraft are riddled with them as they monitor position, wind speed, air pressure, altitude etc. Another important application is for industrial process control where the sensors continually monitor to ensure that efficiency is maximized, production costs are minimized and that waste is reduced.

Sensors are also an integral part of health care and diagnostics. Sensors can determine whether or not biological systems are functioning correctly and most importantly, direct us to act without delay when something is wrong. For instance, glucose meters are playing a crucial role in determining blood sugar levels in people diagnosed with diabetes.

The area of sensor technology is quite broad, and there is considerable diversity in sensor research. In the last four decades sensor research has grown exponentially, largely due to increasing automation, medical applications and escalating use of microelectronics. Parallel to these developments, the capabilities of sensors are increasingly improving as their prices tumble. Sensors have become a ubiquitous part of life, and now more than ever they are playing an important role in our day-to-day lives.

1.3 Nanotechnology Enabled Sensors

Sensor technology is quite possibly the area in which nanotechnology has had one of the greatest impacts. To meet the increasing demands of industry, new approaches to sensor technology have been taken, and this is where nanotechnology shines. Nanotechnology is enabling the development of small, inexpensive and highly efficient sensors, with braod applications.

It is envisaged that by enhancing the interactions that occur at the nanoscale, nanotechnology enabled sensors may offer significant advantages over conventional sensors. This may be in terms of greater sensitivity and selectivity, lower production costs, reduced power consumption as well as improved stability. The unique properties of nanoscale materials make them ideal for sensing. Such materials could be integrated into existing sensing technologies or could be used to form new devices. Not only does nanotechnology enable us to enhance existing materials, it also enables us to fabricate novel materials, whose properties can be tailored specifically for sensing applications.

There exist possibilities for developing nano-bio-organic elements that are suitable for intracellular measurements (Chap. 7). In particular for sensing applications, nanotechnology allows development of nanostructures and the possibility of forming features, the likes of which cannot be imagined with conventional microtechnologies. The characteristics of nanotechnologically enabled sensors are more favorable for sensing than the classically fabricated systems. For example, sensitivity may increase due to tailored conduction properties, the limits of detection may be lowered, infinitely small quantities of samples can be analyzed, direct analyte detection may be possible without using labels, and specificity may be improved (Chaps. 2,6 and 7). Physical sensors, electro-sensors, chemical sensors and biosensors may all benefit from nanotechnology. Using nanotechnological processes, the density of states in materials can be tuned to develop highly sensitive magnetic sensors (Chaps. 2 and 6) or to create quantum resistance which have enormous applications in electronic industry (Chap. 6). Using nanomaterials, highly efficient Peltier transducers can be fabricated which will change the face of the energy industry in a not distant future (Chap. 2).

Improved sensitivity is a major attraction for developing nanotechnology enabled sensors. At the extreme nanoscale limit, there exist the potential to detect a single molecule or atom. The small size, lightweight, and high *surface-to-volume ratio* of nanostructures are the best candidates for improving our capability to detect chemical and biological species with sensitivity that was previously thought to be unattainable. Additionally, in nanostructures the entire structure can be affected by the analyte and not only the surface as conventional sensors **(Fig. 1.4)**.

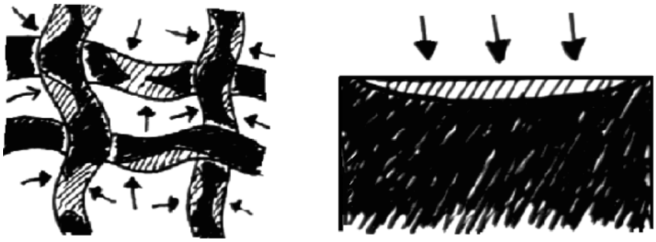


Fig. 1.4 Effect of analytes on nanostructures (left) vs. smooth surfaces (right).

Selectivity is tantamount to sensitivity, yet significantly more difficult to attain. The uses of nanoscale sensors and materials may not implicitly result in greater selectivity; however nanostructuring materials and applying surface modifications and functionalization may greatly assist. Other opportunity which may arise from the employment of nanomaterials includes the deployment of sensor arrays, where multiplicity in the tens to thousands may compensate for the loss of performance of any single measurement.

The speed with which species can be detected is most definitely affected by the sensor's dimensions. Hence, nanoscale modifications present the opportunity for improving the sensor's dynamic performance. Nanostructures minimize the time taken for a measurand to diffuse into and out of that volume **(Fig. 1.4)**. Therefore, this is a key objective of nanotechnology-enabled sensors. For instance, a few seconds may be all the time required to respond to an undesirable and potentially harmful situation. The time taken for the sensor to raise an alarm could be the limiting factor, averting a potential disaster.

Nanotechnology enabled sensors may find applications in numerous fields, however, one of the most significant areas that they will be employed is nano-biotechnology and human health monitoring (Chap. 7).[10] Minimally invasive technologies capable of scanning our bodies for the earliest signs of oncoming of disease are being developed. Their ultimate aim is to create new biomedical technologies that can detect, diagnose and treat diseases inside the human body. Human beings want to live longer, healthier, and happier, be in better control of their bodies, more connected to others and to objects around us. Nanotechnology is one of the tools that may assist humans to reach these goals. *DNA* and *proteins* have been extensively utilized and manipulated by researchers and scientists for biosensing applications (Chap. 7). These natural bio-elements, with embedded intelligence, are ready made nanosized building blocks and tools that can perform pre-programmed functions on demand. They can selectively bind to target molecules and carry out the required alterations. *Redox-ezymatic proteins* are the base of glucose sensors which improve the quality of life for millions afflicted with diabetes (Chaps. 6 and 7).

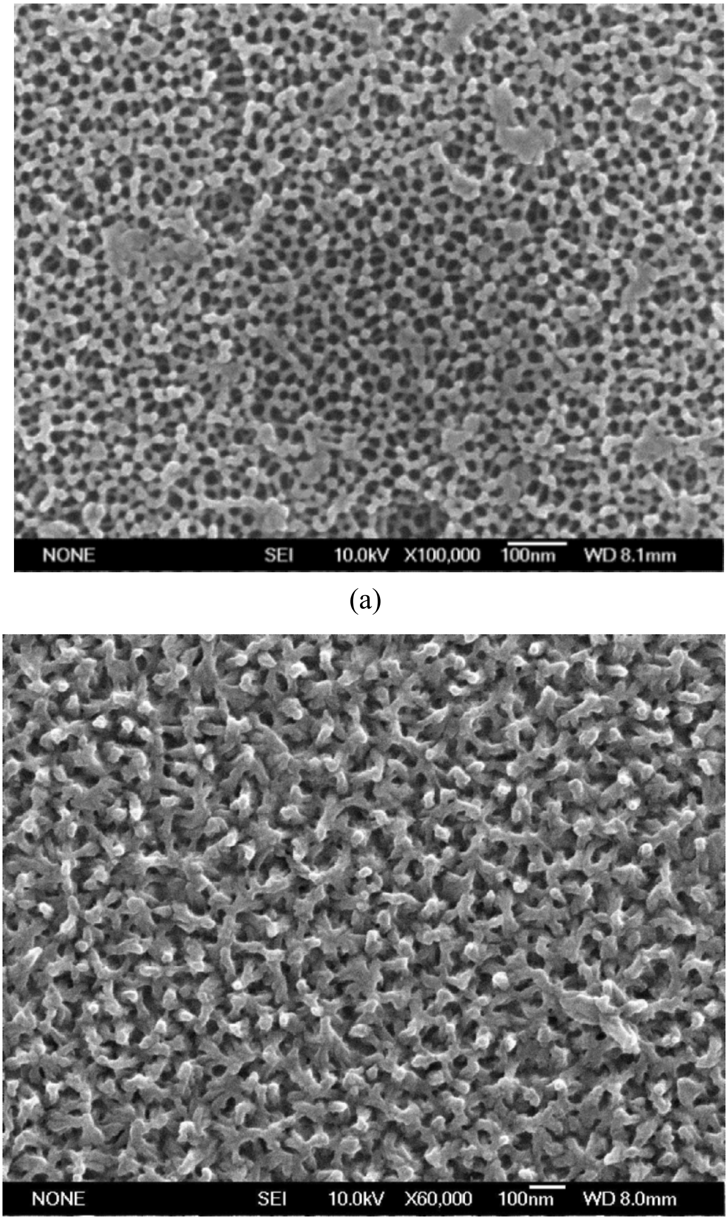
Other good examples highlighting advantages of nanotechnological applications in sensing resides in the fabrication of chemical sensors. Such sensors have traditionally suffered from limited measurement accuracy, sensitivity and plagued with problems of long-term stability. However, recent advances in nanotechnology have resulted in novel classes of nanostructured thin films, similar to those of polyaniline and TiO_2 thin films shown in **Fig. 1.5**. As will be seen in Chaps. 6 and 7, the nanostructured polyaniline, which is a conductive polymer, thin film can be utilized for the fabrication of optical biosensors as well as gas and liquid phase conductometric sensors with ultra fast responses. TiO_2 nanostructured thin films can be employed as gas sensitive film in conductometric sensors, as an efficient photocatalyst in optical sensors and cells and as metal oxide which provide superhydrophobicity for the immobilization of proteins.

Such nanostructured thin films enhance chemical sensing properties via an increased surface area to volume ratio, improving the active sensing area available for the interaction with the target molecules (Chaps. 2-7). Additionally, strong photon and phonon quenching and amplification are also observed for such surfaces that cannot be seen in conventional bulk materials (Chaps. 6 and 7). With such alterations the optical and electronic properties can be tailored to suit the applications.

Using the nanoparticles, it is possible to tune and amplify the response of optical sensors for narrow frequency bands which makes them more accurate and selective. They can resonate with the same stimuli at different frequencies, a property which can be highly useful in medical imaging for differentiating discerning between different targets. Surface of nanoparticles can be functionalized for specific biosensing applications.

The market for nanotechnology enabled sensors is constantly growing. Advances in technology will further facilitate the nanotechnologically enabled sensors' incorporation with sophisticated electronics signal processing with innovative transducers and actuators, electronic components, communication circuits and in medical sciences.

There are already many nanotechnology enabled sensors in the market. However, in the following decades the smarter, cheaper and more selective and sensitive sensors will influence our lives much more and their applications will become more pronounced in our daily lives.



(b)

Fig. 1.5 Scanning electron micrographs of (a) anodized nanoporous TiO_2 (b) polyaniline nanofibers electrodeposited on gold.

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Chapter 2: Sensor Characteristics and Physical Effects

2.1 Introduction

The potential of nanotechnology enabled sensors was highlighted in the previous chapter. In this chapter, the fundamental characteristics and terminologies associated with transducers and sensors are introduced. Furthermore, some of the major effects that are utilized in sensing for the conversion of energy from a measurand (the physical parameter being quantified by a measurement) to a measurable signal are described. These effects illustrate the relationship between different physical and chemical phenomena that can be measured using sensors. This will be a prelude to Chap. 3, which focuses on major transduction platforms.

The essence of Chap. 2 is on physical transduction phenomena. The majority of chemical phenomena which are related to nanotechnology enabled sensing can be found in Chaps. 6 and 7.

2.2 Sensor Characteristics and Terminology

A *sensor* is a device that produces a measurable signal in response to a stimulus. A *transducer* is a device that converts one form on energy into another. Generally, a sensing or sensitive layer/medium directly responds to the external stimulus, while the transducer converts the response into an external measurable quantity. As distinct from *detectors,* sensors are employed to monitor and quantify changes in the measurand, whereas detectors simply indicate the presence of the measurand.[1,2]

The characteristics of a sensor may be classified as being either *static*, or *dynamic*. These parameters are essential in high fidelity mapping of output versus input. Static characteristics are those that can be measured after all transient effects have stablized to their final or steady state. They address questions such as; by how much did the sensor's output change in response to the input? what is the smallest change in the input that will give an output reading? and how long did it take for the output value to change to the present value? Dynamic characteristics describe the sensor's transient properties. These typically address questions such as; at what rate is the output changing in response to the input? and what impact would a slight change in the input conditions have on the transient response?

2.2.1 Static Characteristics

Accuracy:

This defines how correctly the sensor output represents the true value. In order to assess the accuracy of a sensor, either the measurement should be benchmarked against a standard measurand or the output should be compared with a measurement system with a known accuracy. For instance, an oxygen gas sensor, which operates at a room with 21% oxygen concentration, the gas measurement system is more accurate if it shows 21.1% rather than 20.1% or 22%.

Error:

It is the difference between the true value of the quantity being measured and the actual value obtained from the sensor. For instance, in the gas sensing example, if we are measuring the oxygen content in the room having exactly 21% oxygen, and our sensor gives us a value of 21.05%, then the error would be 0.05%.

Precision:

Precision is the estimate which signifies the number of decimal places to which a measurand can be reliably measured. It relates to how carefully the final measurement can be read, not how accurate the measurement is.

Resolution:

Resolution signifies the smallest incremental change in the measurand that will result in a detectable increment in the output signal. Resolution is strongly limited by any noise in the signal.

Sensitivity:

Sensitivity is the ratio of incremental change in the output of the sensor to its incremental change of the measurand in input. For example, if we have a gas sensor whose output voltage increases by 1 V when the oxygen concentration increases by 1000 ppm, then the sensitivity would be 1/1000 V/ppm, or more simply 1 mV/ppm.

Selectivity:

A sensor's ability to measure a single component in the presence of others is known as its selectivity. For example, an oxygen sensor that does not show a response to other gases such as CO, CO_2 and NO_2, may be considered as selective.

Noise:

Noise refers to random fluctuations in the output signal when the measurand is not changing. Its cause may be either internal or external to the sensor. Mechanical vibrations, electromagnetic signals such as radio waves and electromagnetic noise from power supplies, and ambient temperatures, are all examples of external noise. Internal noises are quite different and may include:

1. *Electronic Noise*, which results from random variations in current or voltage. These variations originate from thermal energy, which causes charge carriers to move about in random motions. It is unavoidable and present in all electronic circuits.
2. *Shot Noise*, which manifests as the random fluctuations in a measured signal, caused by the signal carriers' random arrival time. These signal carriers can be electrons, holes, photons, etc.
3. *Generation-Recombination Noise*, or *g-r noise*, that arises from the generation and recombination of electrons and holes in semiconductors.
4. *Pink Noise*, also known as *1/f noise*, is associated with a frequency spectrum of a signal, and has equal power per octave. The noise components of the frequency spectrum are inversely proportional to the frequency. Pink noise is associated with self-organizing, bottom-up systems that occur in many physical (e.g. meteorological: thunderstorms, earthquakes), biological (statistical distributions of DNA sequences, heart beat rhythms) and economical systems (stock markets).

Drift:

It is the gradual change in the sensor's response while the measurand concentration remains constant. Drift is the undesired and unexpected change that is unrelated to the input. It may be attributed to aging, temperature instability, contamination, material degradation, etc. For instance, in a gas sensor, gradual change of temperature may change the baseline stability, or gradual diffusion of the electrode's metal into substrate may change the conductivity of a semiconductor gas sensor which deteriorating its baseline value.

Minimum Detectable Signal (*MDS*):

This is the minimum detectable signal that can be extracted in a sensing system, when noise is taken into account. If the noise is large relative to the input, it is difficult to extract a clear signal from the noise.

Detection Limit:

It is the smallest magnitude of the measurand that can be measured by a sensor.

Repeatability:

Repeatability is the sensor's ability to produce the same response for successive measurements of the same input, when all operating and environmental conditions remain constant.

Reproducibility:

The sensor's ability to reproduce responses after some measurement condition has been changed. For example, after shutting down a sensing system and subsequently restarting it, a reproducible sensor will show the same response to the same measurand concentration as it did prior to being shut down.

Hysteresis:

It is the difference between output readings for the same measurand, when approached while increasing from the minimum value and the other while decreasing from the peak value.

Stability:

The sensor's ability to produce the same output value when measuring a fixed input over a period of time.

Response Time:

The time taken by a sensor to arrive at a stable value is the response time. It is generally expressed as the time at which the output reaches a certain percentage (for instance 95%) of its final value, in response to a stepped change of the input. The *recovery time* is defined in a similar way but conversely.

Dynamic Range or Span:

The range of input signals that will result in a meaningful output for the sensor is the dynamic range or span. All sensors are designed to perform over a specified range. Signals outside of this range may be unintelligible, cause unacceptably large inaccuracies, and may even result in irreversible damage to the sensor.

2.2.2 Dynamic Characteristics

It is advantageous to use *linear* and *time invariant* mathematical representations for sensing systems. Such representations have been widely studied, they are easy to extract information from and give an overall vision about the sensing systems to the users. The relationship between the input and output of any linear time invariant measuring system can be written as:

$$a_n \frac{d^n y(t)}{dt^n} + a_{n-1} \frac{d^{n-1} y(t)}{dt^{n-1}} + \ldots + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_m \frac{d^{m-1} x(t)}{dt^m} + b_{m-1} \frac{d^{m-1} x(t)}{dt^{m-1}} + \ldots + b_1 \frac{dx(t)}{dt} + b_0 x(t), \quad (2.1)$$

where $x(t)$ is the measured quantity (input signal) and $y(t)$ is the output reading and $a_0, \ldots, a_n, b_o, \ldots, b_m$ are constants.

$x(t)$ can have different forms and values. As a simple and commonly encountered example in sensing systems, $x(t)$ may be considered to be a *step change* (*step function*) similar to that depicted in **Fig. 2.1**. However, on many occasions this is an over simplification, as there is generally a rise and fall time for the step input to occur.

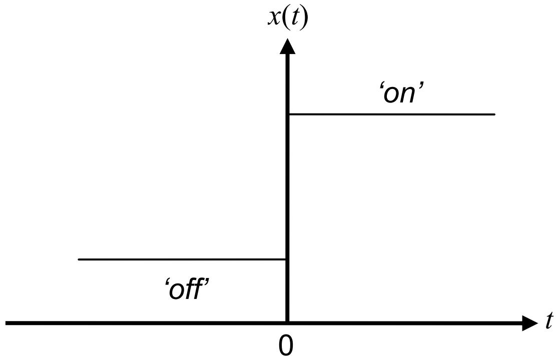

Fig. 2.1 A step change.

When the input signal is a step change, Eq. (2.1) reduces to:

$$a_n \frac{d^n y(t)}{dt^n} + a_{n-1} \frac{d^{n-1} y(t)}{dt^{n-1}} + ... + a_1 \frac{dy(t)}{dt} a_{n-1} + a_0 y(t) = b_0 x(t), \tag{2.2}$$

as all derivatives of $x(t)$ with respect to t are zero. The input does not change with time except at $t = 0$. Further simplifications can be made. For instance, if output shows an instantaneous response to the input signal then all $a_1, ..., a_n$ coefficients except a_0 are zero, as a result:

$$a_0 y(t) = b_0 x(t) \text{ or simply: } y(t) = Kx(t). \tag{2.3}$$

where $K = b_0 / a_0$ is defined as the static sensitivity. Such a response represents a perfect zero order system. If the system is not perfect and the output does show a gradual approach to its final value, then it is called a first order system. A simple example of a first order system is the charging of a capacitor with a voltage supply, whose rate of charging is exponential in nature. Such a first order system is described by the following:

$$a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_0 x(t), \tag{2.4}$$

or after rearranging:

$$\frac{a_1}{a_0} \frac{dy(t)}{dt} + y(t) = \frac{b_0}{a_0} x(t). \tag{2.5}$$

By defining $\tau = a_1/a_0$ as the time constant, the equation will take the form of a *first order ordinary differential equation* (*ODE*):

$$\tau \frac{dy(t)}{dt} + y(t) = Kx(t)\,. \tag{2.6}$$

This ODE can be solved by obtaining the homogenous and particular solutions. Solving this equation reveals that the output $y(t)$ in response to $x(t)$ changes exponentially. Furthermore, τ is the time taken for the output value to reach 63% of its final value, i.e. $(1\text{-}1/e^{-1}) = 0.6321$, as seen in a typical output of a first order system in **Fig. 2.2**.

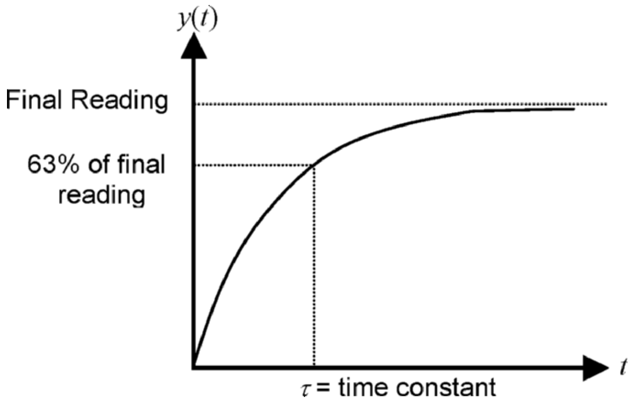

Fig. 2.2 Graphical depiction of a first order system's response with a time constant of τ.

On the other hand, the response of a *second order system* to a step change can be defined as:

$$a_2 \frac{d^2 y(t)}{dt^2} + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_0 x(t)\,\cdot \tag{2.7}$$

By defining the undamped natural frequency $\omega = a_0/a_2$, and the damping ratio $\varepsilon = a_1/(2a_0a_2)$, Eq. (2.7) reduces to:

$$\frac{1}{\omega^2}\frac{d^2 y(t)}{dt^2} + \frac{2\varepsilon}{\omega}\frac{dy(t)}{dt} + y(t) = Kx(t)\,\cdot \tag{2.8}$$

This is a standard second order system. The damping ratio plays a pivotal role in the shape of the response as seen in **Fig. 2.3**. If $\varepsilon = 0$ there is no damping and the output shows a constant oscillation, with the solution being a sinusoid. If ε is relatively small then the damping is light, and the oscillation gradually diminishes. When $\varepsilon = 0.707$ the system is *critically*