Solid-State Physics, Fluidics, and Analytical Techniques in Micro- and Nanotechnology

BOOK 1 of The Fundamentals of Microfabrication and Nanotechnology, Third Edition, Three-Volume Set

Chapter 1: Historical Note: The Ascent of Si, MEMS, and NEMS

1.1:

Why is silicon so important to MEMS and NEMS?

Answer:

Compared with other materials, silicon has the following advantages in MEMS applications:

1. Wide use within the microelectronic IC industry with fabrication processes that are well developed. Design and fabrication tools are also readily available and quite economical to use.
2. Excellent electrical properties.
3. Excellent mechanical material that is well understood and controllable.
4. Excellent native oxide (SiO_2).
5. Inexpensive and abundant.
6. Electronics and MEMS can be integrated on the same chip.
7. Very well understood isotropic and anisotropic wet etching behavior.

1.2:

Compare the pros and cons of transistors and vacuum tubes.

Answer:

For decades before the arrival of the transistor, it was the vacuum tube that formed an integral part of all electronic devices. Like transistors today, vacuum tubes were used as switches and amplifiers. However, there were many practical problems associated with the vacuum tube: it was expensive, noisy, slow, large, and dissipated a lot of heat. The transistor was the perfect replacement for the vacuum tube. They were not only cheaper, but also smaller, and more reliable. The invention of the transistor and later that of the integrated circuit which allowed for millions of transistors to be packed together on a single silicon chip, enabled components to work at lightening-fast pace. Transistors and vacuum tubes are compared in the following table.

Transistors vs. Vacuum tubes

Transistor	Vacuum Tube
Inexpensive	Expensive
Excellent reliability	Unreliable
Very small	Large and bulky
Stable temperatures	Gets hot quickly
Very fast	Slow
Can be made in very large numbers	Found in small numbers
Cannot carry very high voltage	Can carry high voltage (Main factor responsible for the survival of vacuum tubes in some appliances)

1.3:

Why was the Si-MEMS market at one point in time expected to be much larger than the IC market?

Answer:

The expectation in the late 1980s was that most Si-MEMS devices would feature sensors, actuators, and electronics integrated on a single Si chip. Up to that point, ICs were used as logic elements and amplifiers only. The integration of sensors and actuators with ICs would broaden the application range of ICs dramatically so the expectation was that the market would become larger than that of ICs. The integration of ICs with sensor and actuators has proven to be much more difficult than anticipated and the MEMS market is, even today, only about 10% the size of the IC market.

1.4:

Can you list some of the current technological and economic barriers that restrict the wider commercialization of Si-MEMS?

Answer:

1. The diversity of sensor and actuator applications has delayed/prevented standardization of manufacturing processes.
2. Packaging of MEMS is much more complex than of ICs.
3. The integration of new materials in MEMS poses all types of process compatibility challenges.
4. For disposables the Si process is often too expensive.
5. Absence of foundry facilities that carry out non-traditional processes.
6. Calibration/testing of MEMS is much more expensive and very application specific.
7. Good CAD packages are difficult to find as MEMS devices are so very application specific.
8. Not enough mass consumer products require MEMS yet (this is changing fast though as MEMS are now found in consumer products ranging from PCs to iPods).

1.5:

(a) State Moore's first law (we are talking about Moore, Intel's cofounder).

(b) What is Moore’s second law?

Answer:

(a) Moore's first law is not really a law but an observation. An observation by Gordon Moore, a co-founder of Intel, that the computing power available on a given chip (or, in a variant, the power available for a given price) doubles every eighteen months. Moore made his assertion at the dawn of the semiconductor age, in the 1960s. Since the early

1990s he and everyone else in the technology business have wondered when this “law” would hit a roadblock. Extreme UV lithography (EUVL) probably gives Moore's Law at least another ten years.

(b) Moore's second law states that as circuitry lines grow closer the development costs increase geometrically.

1.6:
Why did surface micromachining catch on so fast with the IC industry?

Answer:
Surface micromachining is quite compatible with traditional IC manufacturing processes (more so than bulk micromachining), poly-Si used in surface micromachining was already used in the IC industry, and most of the same equipment used in the IC industry can thus be used in surface micromachining. Moreover IC modelling and design software can be used. One also should not underestimate the importance of early DARPA funding and the Multi-User MEMS Process, or MUMPs®, a commercial program, started in December 1992, which provides customers with cost-effective access to surface micromachining for proto-typing activities.

1.7:
Why are MEMS market forecasts so difficult to prepare? How would you go about making a better MEMS market forecast?

Answer:
The volatility of the MEMS market is based on the fact that the same companies that depend on venture capital or government funding for their survival often make market projections in the field. Needless to say that most of these claims are exaggerated. A lot of the MEMS companies go out of business before they even start producing. On the other hand, if they do go into production, the projected pricing of their items tends to be unrealistically optimistic until they are faced with market reality (an example of that is large count optical MEMS switching). The market predictions that are more reliable are those based on the number of competing non-MEMS parts sold on a per year basis.

1.8:
How does radar work? How is it useful?

Answer:
Radar uses a pulse of radio energy to establish the distance based on the time it takes for a pulse to return from a target to the source. Radar has greatly changed the way we see the land and ocean surfaces. Radar is based on the principle of sending very long wavelength radiation (called microwaves) from an antenna, and then detecting that energy after it bounces off a remote target. The wavelength of the microwave, its polarization (vertical or horizontal orientation), and strength can be controlled at the source and measured when it returns. Many common land-cover types and materials affect the polarity and strength of the radar return differently, which helps in their identification.

1.9:

What is the biggest advantage Ge has over Si IC circuits?

Answer:
Ge has a better carrier mobility (in cm^2/V-s) [3900(electron), 1900(hole)] than Si [1500(electron), 450(hole)].

1.10:
What is a strain gauge and what is its gauge factor?

Answer:
Strain gauges are designed to convert mechanical motion into an electronic signal. A change in capacitance, inductance, or resistance is proportional to the strain experienced by the sensor. If a wire is held under tension, it gets slightly longer and its cross-sectional area is reduced. This changes its resistance (R) in proportion to the strain sensitivity (S) of the wire's resistance. The product of the gauge factor (G) or strain factor and strain (ε) equals the ratio of change in strain gauge electrical resistance (ΔR) over the unstrained electrical resistance of the strain gauge ®:

$$\varepsilon G = \frac{\Delta R}{R} \text{ or also } G = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\varepsilon}$$

where
ε = strain
ΔR = change in resistance of the strained strain gauge
R = unstrained resistance of strain gauge

1.11:
What is the definition of nanotechnology?

Answer:
The criteria we use in this book for classifying a system as a nano electromechanical system (NEMS) is not only that the miniaturized structure has at least one dimension that is smaller than 100 nanometers, but also that it is crafted with a novel technique or has been designed intentionally with a specific nano feature in mind (so medieval church stained-glass is out). This definition fits well within the one adopted by the National Nanotechnology Institute (NNI) (http://www.nano.gov/):

1. Nanotechnology involves R&D at the 1 nm-to-100 nm range
2. Nanotechnology creates and uses structures that have novel size based properties
3. Nanotechnology takes advantage of the ability to control or manipulate at the atomic scale

(http://www.nano.gov/html/facts/whatIsNano.html).

1.12
List at least five commercial products that incorporate nanotechnology.

Answer:

1. Probably the most visible nanotech products to date are the stain- and wrinkle-resistant slacks developed by Greensboro, North Carolina-based Nano-Tex LLC and sold by Eddie Bauer, Lee Jeans, and several other retailers.
2. On the ski slopes, VailSoft's Cerax "racing polymers" claim to provide greater speed and control than conventional ski waxes due to a nanotech structure in the wax that holds up in a wide variety of snow conditions.
3. Sunscreen makers have found that zinc oxide—the dense white cream lifeguards put on their noses—turns transparent and silky when made from smaller particles, which cover the skin more thoroughly and do not reflect light. Procter and Gamble has added tiny zinc oxide particles to its Olay Complete UV Protective Moisture Lotion, a product aimed at mall matrons rather than beach bums.
4. The German company Neosino AG markets a nutritional supplement, called "Nanosilimagna," containing calcium, silicon, and magnesium, in which the elements concerned are said to be in the form of nanoparticles (3–10 nm), and for which the company claims absorbability superior to that of other physical forms of the same elemental nutrients.
5. One of the most innovative new products is one that enhances biological imaging for medical diagnostics and drug discovery. Quantum dots are semiconducting nanocrystals that, when illuminated with ultraviolet light, emit a vast spectrum of bright colors that can be used to identify and locate cells and other biological activities. These crystals offer optical detection up to a thousand times brighter than conventional dyes used in many biological tests, such as MRIs, and render significantly more information.
6. Nanoparticles also are being used increasingly in catalysis, where the large surface area per unit volume of nanosized catalysts enhances reactions. Greater reactivity of these smaller agents reduces the quantity of catalytic materials necessary to produce desired results. The oil industry relies on nanoscale catalysts for refining petroleum, while the automobile industry is saving large sums of money by using nanosized—in place of larger—platinum particles in its catalytic converters.

1.13

What year was the word “nanotechnology” first used?

Answer:

Norio Taniguchi introduced the term “nanotechnology” in 1974, in the context of traditional machining with tolerances below 1 micron.

1.14

What was Feynman‘s role in catalyzing the genesis of MEMS and NEMS?

Answer:

The 1959 Feynman lecture “There’s Plenty of Room at the Bottom,” which helped launch the MEMS field, was actually geared more towards NEMS than MEMS (http://www.its.caltech.edu/~feynman/plenty.html). Feynman proclaimed that he knew of no principles of physics that would prevent the direct manipulating of individual atoms. In his top-down *gedanken* experiment he envisioned a series of machines, each an exact duplicate, only smaller and smaller, with the smallest in the series being able to manipulate individual atoms.

1.15

Why was the honeymoon with the transistor over so quickly? What technology took over very fast?

Answer:

The honeymoon with the transistor was quickly over because by the second half of the 1950s, new circuits on the drawing board were so big and complex that it was virtually impossible to wire that many different parts together reliably. A circuit with 100,000 components easily required 1 million, mostly manual, soldering operations that were time consuming, expensive, and inherently unreliable. The answer was the "monolithic" idea in which a single bloc of semiconductor is used for all the components and interconnects, invented by two engineers working at competing companies: Jack Kilby at Texas Instruments and Robert Noyce at Fairchild Semiconductor.

1.16

What does ITRS stand for? What does it mean?

Answer:

ITRS stands for the International Technology Roadmap for Semiconductors. In this technology road map, technology modes have been defined. These modes are the feature sizes that are expected to be in volume manufacturing at a fixed date (year of production). The feature size is defined as half pitch, i.e., half of a dense pair of lines and spaces.

1.17

List a number of nanostructures that have been fabricated with bottom-up methodologies.

Answer:

1. Self-assembled monolayers (SAMs)
2. Dendrimers
3. Crystals
4. DNA and proteins
5. Carbon nanotubes and buckyballs
6. CdSe quantum dots
7. Atom writing with STM tools

1.18

What is a photonic crystal?

Answer:

Imposing boundaries on photons, by making them move in a material with a periodic dielectric constant in one, two, or three directions defines photonic crystals. A one-dimensional periodic structure, such as a multilayer film (a Bragg mirror), is the simplest type of photonic crystal. The possibility of two- and three-dimensionally periodic crystals with corresponding two- and three-dimensional band gaps was suggested by Eli Yablonovitch and Sajeev John in 1987. In photonic crystals the repeat unit in the lattice is of the same size as the incoming wavelength. Photonic crystals feature lattice spacings ranging from the macroscopic (say 1 mm, for operating in the micro-wave domain) to the 100s of nanometer range (to operate in the visible range). The potential applications of photonics are limitless, not only as a tool for controlling quantum optical systems, but also in more efficient miniature lasers for displays and telecommunications, in solar cells, LEDs, optical fibers, nanoscopic lasers, ultra-white pigments, radio frequency antennas and reflectors, photonic integrated circuits, etc.

1.19
What is a metamaterial?

Answer:
Metamaterials are artificially engineered materials possessing properties that are not encountered in nature (e.g., a negative refractive index ε and a negative magnetic permeability μ). Whereas photonic materials do exist in nature, metamaterials do not; moreover in the case of metamaterials the building blocs are small compared to the incoming wavelength so that effective media theory can be applied.

1.20
What are the important differences between typical devices made in the IC industry and MEMS?

Answer:
1. The aspect ratio (height to width) of the features in MEMS is typically much higher than in IC industry.
2. MEMS devices incorporate many new, non-IC materials.
3. Packaging in MEMS is much more complicated than for an IC.
4. Feature sizes are typically larger in MEMS devices.
5. MEMS devices are much more application specific than ICs.
6. Many MEMS devices are disposable.
7. Si is not the main material in MEMS.