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Introduction

1.1 HISTORICAL DEVELOPMENT OF MICROELECTRONICS

The field of microelectronics began in 1948 when the first transistor was invented. This first transistor was a point-contact transistor, which became obsolete in the 1950s following the development of the bipolar junction transistor (BJT). The first modern-day junction field-effect transistor (JFET) was proposed by Shockley (1952). These two types of electronic devices are at the heart of all microelectronic components, but it was the development of integrated circuits (ICs) in 1958 that spawned today's computer industry.

IC technology has developed rapidly during the past 40 years; an overview of the current bipolar and field-effect processes can be found in Chapter 4. The continual improvement in silicon processing has resulted in a decreasing device size; currently, the minimum feature size is about 200 nm. The resultant increase in the number of transistors contained within a single IC follows what is commonly referred to as *Moore's law*. Figure 1.1 shows that in just 30 years the number of transistors in an IC has risen from about 100 in 1970 to 100 million in 2000. This is equivalent to a doubling of the number per chip every 18 months. Figure 1.1 plots a number of different common microprocessor chips on the graph and shows the clock speed rising from 100 kHz to 1000 MHz as the chip size falls. These microprocessors are of the type used in common personal computers costing about €1000 in today's prices¹.

Memory chips consist of transistors and capacitors; therefore, the size of dynamic random access memories (DRAM) has also followed Moore's law as a function of time. Figure 1.2 shows the increase of a standard memory chip from 1 kB in 1970 to 512 MB in 2000. If this current rate of progress is maintained, it would be possible to buy for €1000 a memory chip that has the same capacity as the human brain by 2030 and a memory chip that has the same brain capacity as everyone in the whole world combined by 2075! This phenomenal rise in the processing speed and power of chips has resulted first in a computer revolution and currently in an information revolution. Consequently, the world market value of ICs is currently worth some 250 billion euros, that is, about 250 times their processing speed in hertz.

¹ 1 euro (€) is currently worth about 1 US dollar.

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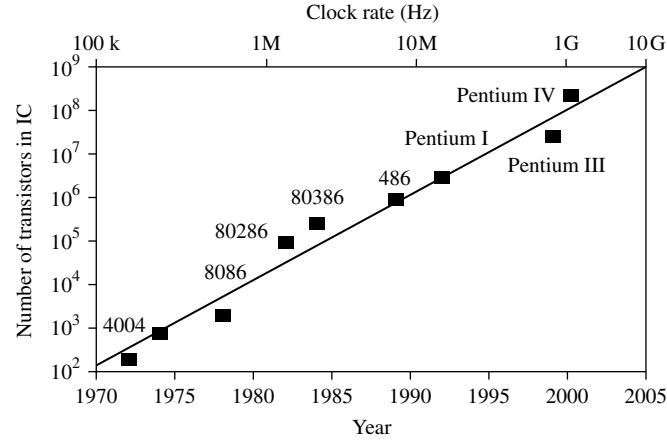


Figure 1.1 Moore's law for integrated circuits: exponential growth in the number of transistors in an IC during the past 30 years

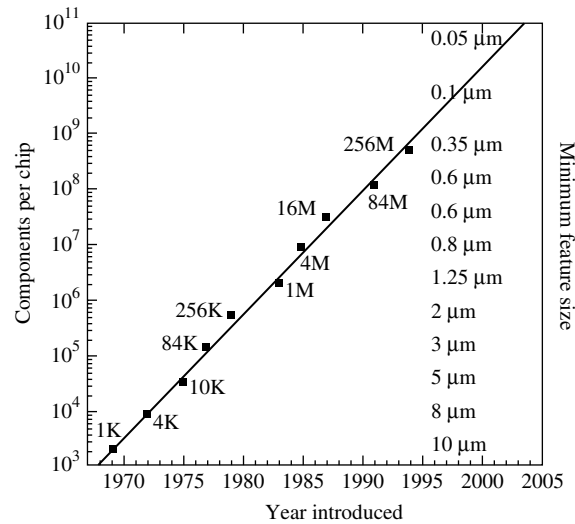


Figure 1.2 Size of memory chips (DRAM) and minimum feature as a function of time. From Campbell (1996)

1.2 EVOLUTION OF MICROSENSORS

The microelectronics revolution has led to increasingly complex signal–data processing chips; this, remarkably, has been associated with falling costs. Furthermore, these processing chips are now combined with sensors and actuators² to make an information-processing triptych (see Figure 1.3). These developments follow the recognition in the

² A sensor is a device that normally converts a nonelectrical quantity into an electrical quantity; an actuator is the converse. See Appendix C for the definition of some common terms.

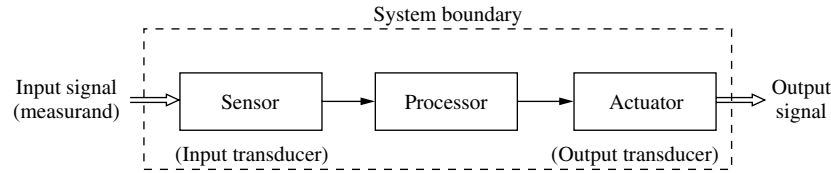


Figure 1.3 The information-processing triptych. From Gardner (1994)

1980s that the price-to-performance ratio of both sensors and actuators had fallen woefully behind processors. Consequently, measurement systems tended to be large and, more importantly, expensive. Work therefore started to link the microelectronic technologies and use these to make silicon sensors, the so-called microsensors.

Working definition of the term sensor:

'A microsensor is a sensor that has at least one physical dimension at the submillimeter level.'

This work was inspired by the vision of microsensors being manufactured in volumes at low cost and with, if necessary, integrated microelectronic circuitry. Chapters 5 and 6 describe in some detail the silicon micromachining technologies used today to make microsensors and microactuators. An overview of the field of microsensors is given in Chapter 8.

Figure 1.4 shows the relative market for ICs and microsensors in the past 10 years. It is evident that the market for microsensors lags well behind the market for ICs; nevertheless, it is worth 15 to 20 billion euros. The main cause has been the relatively stable price–performance (p/p) ratio of sensors and actuators since 1960, as illustrated in Figure 1.5. This contrasts markedly with the p/p ratio of ICs, which has fallen enormously between 1960 and 2000 and is now significantly below that for sensors and actuators. As a consequence of these changes, the cost of a measurement system is, in general, dominated first by the cost of the microactuator and second by the cost of the microsensor.

However, despite the cost advantages, there are several major technical advantages of making microsensors with microsystems technology (MST); the main ones are as follows:

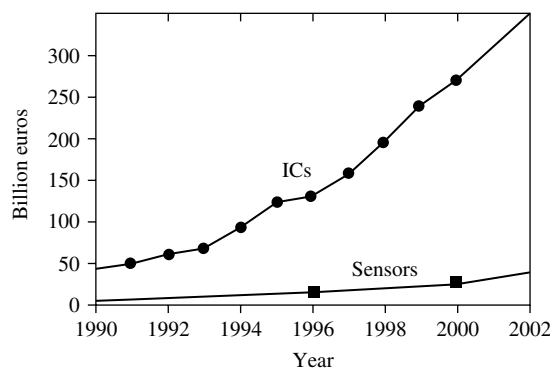


Figure 1.4 World market for ICs and microsensors from 1990 to 2000. From various sources

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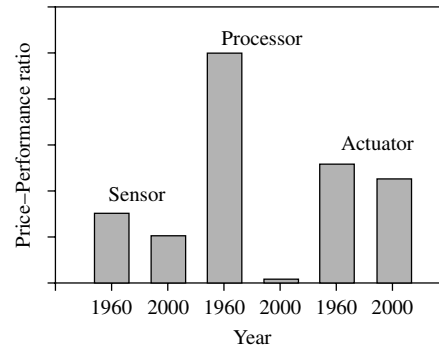


Figure 1.5 Price-performance indicators for ICs, sensors, and actuators

- The employment of well-established microtechnology
- The production of miniature sensors
- The production of less bulky and much lighter sensors
- The batch production of wafers for high volume
- The integration of processors

The UK marketplace for microsensors is diverse, as shown in Figure 1.6, and includes processing plants – environment and medical. However, the largest sector of the world (rather than UK) sensor market³ is currently automotive; in 1997, the sales of pressure

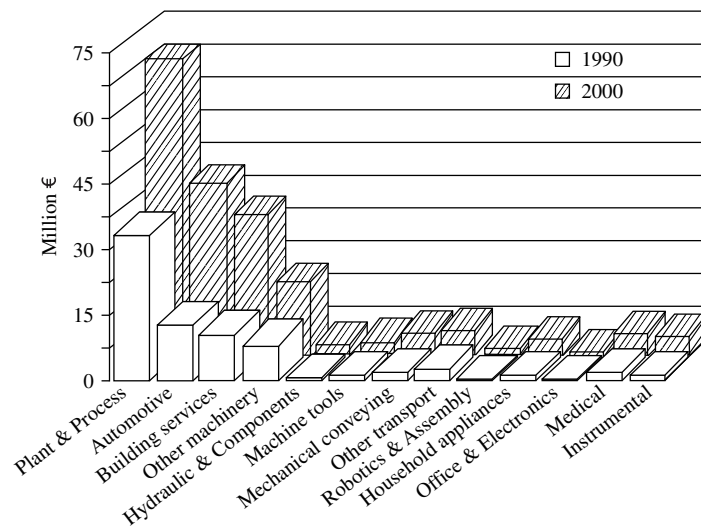


Figure 1.6 Sensor market by application for the United Kingdom. From Gardner (1994)

³ These figures relate to the sensor market and hence exclude the larger markets for disk and ink-jet printer heads.

sensors was about 700 million euros and that for accelerometers was about 200 million euros (see Tables 8.10 and 8.11).

As the market for automotive sensors has matured, the price has fallen from €100 to €10 for a pressure sensor. In addition, the sophistication of the chips has increased and so has the level of integration. How this has led to the development of ‘smart’ sensors is discussed in Chapter 15.

Working definition of the term smart sensor:

‘A smart sensor is a sensor that has part or its entire processing element integrated in a single chip.’

1.3 EVOLUTION OF MEMS

The next ambitious goal is to fabricate monolithic or integrated chips that can not only sense (with microsensors) but also actuate (with microactuators), that is, to create a microsystem that encompasses the information-processing triptych. The technology employed to make such a microsystem is commonly referred to as MST. Figure 1.7 provides an overview of MST together with some of the application areas. Work to achieve this goal started in the late 1980s, and there has been enormous effort to fabricate microelectromechanical systems (MEMS) using MST.

Working definition of the term MEMS:

‘A MEMS is a device made from extremely small parts (i.e. microparts).’

Early efforts focused upon silicon technology and resulted in a number of successful micromechanical devices, such as pressure sensors and ink-jet printer nozzles. Yet, these are, perhaps, more accurately described as devices rather than as MEMS. The reason

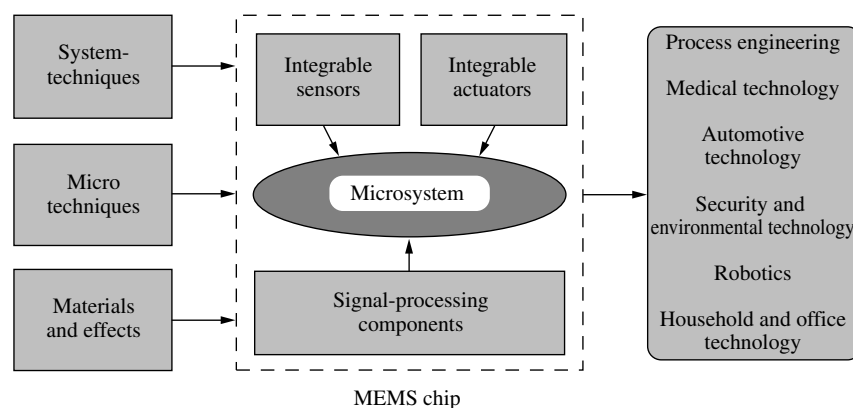


Figure 1.7 Overview of microsystems technology and the elements of a MEMS chip. From Fatikow and Rembold (1997)

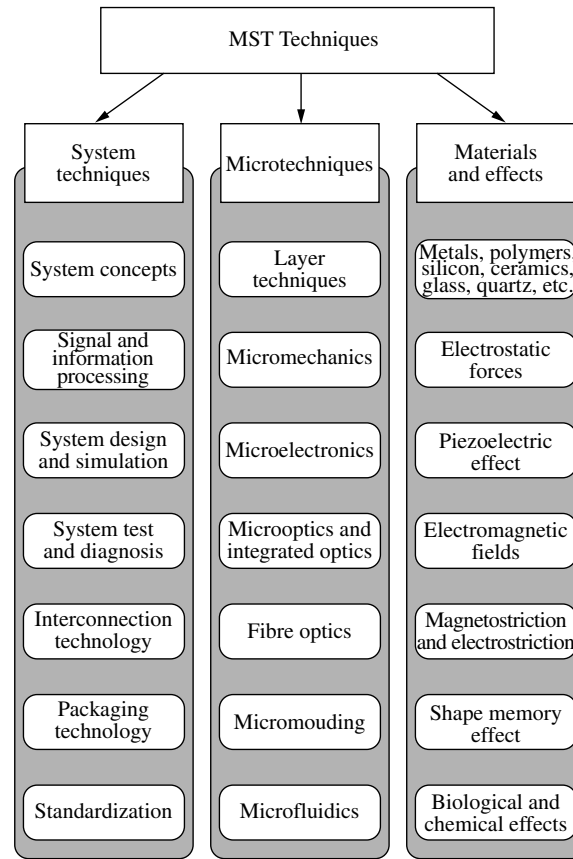


Figure 1.8 Some of the many fundamental techniques required to make MEMS devices. From Fatikow and Rembold (1997)

for the relatively slow emergence of a complete MEMS has been the complexity of the manufacturing process. Figure 1.8 details some new materials for MEMS and the various microtechnologies that need to be developed.

In Chapter 3, some of the new materials for MEMS have been introduced and their fundamental properties have been described. One attractive solution to the development of MEMS is to make all the techniques compatible with silicon processing. In other words, conventional complementary metal oxide semiconductor (CMOS) processing is combined with a pre-CMOS or post-CMOS MST. Because of the major significance of this approach, Chapters 12 to 14 have been dedicated to the topic of interdigitated transducers (IDTs) and their use in microsensors and MEMS devices.

The present MEMS market is relatively staid and mainly consists of some simple optical switches for the communications industry, pressure sensors, and inertial sensors for the automotive industry, as shown in Figure 1.9. This current staidness contrasts with the potential for MEMS, which is enormous. Table 1.1 is taken from a recent report on the world market for MEMS devices. The major growth areas were identified as microfluidics and photonics and communications. However, there have been some exciting

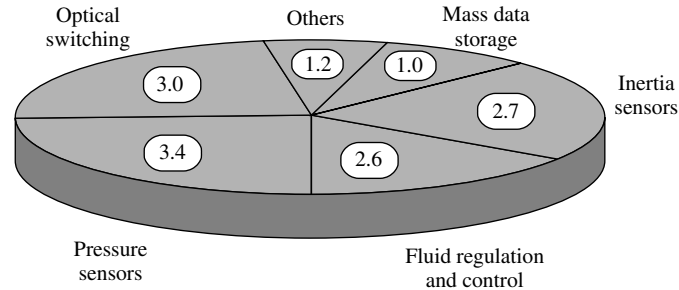


Figure 1.9 Pie chart showing the relative size of the current world MEMS market. The units shown are billions of euros

Table 1.1 Sales in millions of euros of MEMS devices according to the System Planning Corporation Market Survey (1999)

Devices and applications	1996	2003
Ink-jet printers, mass-flow sensors, biolab chips: microfluidics	400–500	3000–4450
Pressure sensors: automotive, medical, and industrial	390–760	1100–2150
Accelerometers and gyroscopes: automotive and aerospace	350–540	700–1400
Optical switches and displays: photonics and communications	25–40	440–950
Other devices such as microrelays, sensors, disk heads	510–1050	1230–2470
TOTAL IN MILLION €	1675–2890	6470–11 420

developments in methods to fabricate true three-dimensional structures on the micron scale. Chapter 7 describes the technique of microstereolithography and how it can be used to make a variety of three-dimensional microparts, such as microsprings, microgears, microturbines, and so on.

There are two major challenges facing us today: first, to develop methods that will manufacture microparts in high volume at low cost and, second, to develop microassembly techniques. To meet these challenges, certain industries have moved away from the use of silicon to the use of glasses and plastics, and we are now seeing the emergence of chips in biotechnology that include microfluidic systems (Chapter 15), which can truly be regarded as MEMS devices.

1.4 EMERGENCE OF MICROMACHINES

Natural evolution will then lead to MEMS devices that move around by themselves. Such chips are commonly referred to as micromachines and the concepts of microplanes, microrobots, microcars, and microsubmarines have been described by Fujimasa (1996). Figure 1.10 shows the scales involved and compares them with the size of a human flea!

Micromachines, if developed, will need sophisticated microsensors so that they can determine their location and orientation in space and proximity to other objects. They should also be able to communicate with a remote operator and hence will require a wireless communication link – especially if they are asked to enter the human body. Wireless communication has already been realised in certain acoustic microsensors, and

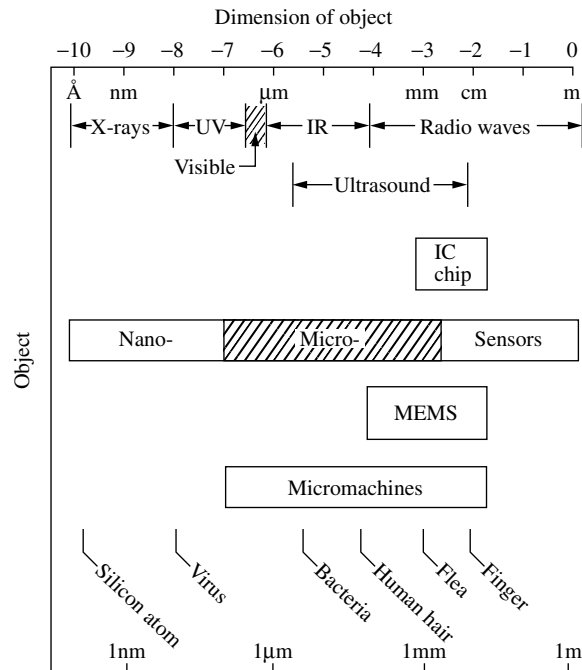


Figure 1.10 Dimensions of microsensors, MEMS, and micromachines; they are compared with some everyday objects. The horizontal axis has a logarithmic scale. Modified from Gardner (1994)

MEMS devices are described in Chapters 13 and 14. Associated with this development, there is a further major problem to solve, namely, miniaturisation of a suitable power source. Moving a micromachine through space requires significant energy. If it is to then do something useful, such as removing a blood clot in an artery, even more power will be required. Consequently, the future of MEMS devices may ultimately be limited by the communication link and the size of its ‘battery pack!’

The road to practicable micromachines appears to be long and hard but the first steps toward microsensors and MEMS devices have been taken, and this book provides an overview of these initial steps.

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