
Materials for MEMS and Microsystems

CHAPTER OUTLINE

- 7.1 Introduction
- 7.2 Substrates and Wafers
- 7.3 Active Substrate Materials
- 7.4 Silicon as a Substrate Material
 - 7.4.1 The Ideal Substrate for MEMS
 - 7.4.2 Single-Crystal Silicon and Wafers
 - 7.4.3 Crystal Structure
 - 7.4.4 The Miller Indices
 - 7.4.5 Mechanical Properties of Silicon
- 7.5 Silicon Compounds
 - 7.5.1 Silicon Dioxide
 - 7.5.2 Silicon Carbide
 - 7.5.3 Silicon Nitride
 - 7.5.4 Polycrystalline Silicon
- 7.6 Silicon Piezoresistors
- 7.7 Gallium Arsenide
- 7.8 Quartz
- 7.9 Piezoelectric Crystals
- 7.10 Polymers
 - 7.10.1 Polymers as Industrial Materials
 - 7.10.2 Polymers for MEMS and Microsystems

7.10.3 Conductive Polymers

7.10.4 The Langmuir–Blodgett (LB) Film

7.11 Packaging Materials

Problems

7.1 | INTRODUCTION

In Chapter 1, we maintained that the current technologies used in producing MEMS and microsystems are inseparable from those of microelectronics. This close relationship between microelectronics and microsystems fabrication often misleads engineers to a common belief that the two are indeed interchangeable. It is true that many of the current microsystem fabrication techniques are closely related to those used in microelectronics. Design of microsystems and their packaging, however, is significantly different from that for microelectronics. Many microsystems use microelectronics materials such as silicon, and gallium arsenide (GaAs) for the sensing or actuating elements. These materials are chosen mainly because they are dimensionally stable and their microfabrication and packaging techniques are well established in microelectronics. However, there are other materials used for MEMS and microsystems products—such as quartz and Pyrex, polymers and plastics, and ceramics—that are not commonly used in microelectronics. Plastics and polymers are also used extensively in the case of microsystems produced by the LIGA processes, as will be described in Chapter 9.

7.2 | SUBSTRATES AND WAFERS

The frequently used term *substrate* in microelectronics means a flat macroscopic object on which microfabrication processes take place [Ruska 1987]. In microsystems, a substrate serves an additional purpose: it acts as signal transducer besides supporting other transducers that convert mechanical actions to electrical outputs or vice versa. For example, in Chapter 2, we saw pressure sensors that convert the applied pressure to the deflection of a thin diaphragm that is an integral part of a silicon die cut from a silicon substrate. The same applies to microactuators, in which the actuating components, such as the microbeams made of silicon in microaccelerators, are also called substrates.

In semiconductors, the substrate is a single crystal cut in slices from a larger piece called a *wafers*. Wafers can be of silicon or other single crystalline material such as quartz or gallium arsenide. Substrates in microsystems, however, are somewhat different. There are two types of substrate materials used in microsystems: (1) active substrate materials and (2) passive substrate materials, as will be described in detail in the subsequent sections.

Table 7.1 presents a group of materials that are classified as electric *insulators* (or dielectrics), *semiconductors*, and *conductors* [Sze 1985]. The same reference classifies the insulators to have electrical resistivity ρ in the range of $\rho > 10^8 \Omega\text{-cm}$; semiconductors with $10^{-3} \Omega\text{-cm} < \rho < 10^8 \Omega\text{-cm}$; and conductors with $\rho < 10^{-3} \Omega\text{-cm}$. We will find that common substrate materials used in MEMS such as silicon

(Si), germanium (Ge), and gallium arsenide (GaAs) all fall in the category of semiconductors. One major reason for using these materials as principal substrate materials in both microelectronics and microsystems is that these materials are at the borderline between conductors and insulators, so they can be made either a conductor or an insulator as needs arise. Indeed, the doping techniques that were described in Chapter 3 can be used to convert the most commonly used semiconducting material, silicon, to an electrically conducting material by doping it with a foreign material to form either p- or n-type silicon for conducting electricity. All semiconductors are amenable to such doping. Another reason for using semiconductors is that the fabrication processes, such as etching, and the equipment required for these processes have already been developed for these materials.

A checklist of factors that help the designer in selecting substrate materials for microsystems is available in Madou [1997].

Table 7.1 | Typical electrical resistivity of insulators, semiconductors, and conductors

Materials	Approximate electrical resistivity ρ_r , $\Omega\text{-cm}$	Classification
Silver (Ag)	10^{-6}	Conductors
Copper (Cu)	$10^{-5.8}$	
Aluminum (Al)	$10^{-5.5}$	
Platinum (Pt)	10^{-5}	
Germanium (Ge)	$10^{-3}\text{--}10^{1.5}$	Semiconductors
Silicon (Si)	$10^{-3}\text{--}10^{4.5}$	
Gallium arsenide (GaAs)	$10^{-3}\text{--}10^9$	
Gallium phosphide (GaP)	$10^{-2}\text{--}10^{6.5}$	
Oxide	10^9	Insulators
Glass	$10^{10.5}$	
Nickel (pure)	10^{13}	
Diamond	10^{14}	
Quartz (fused)	10^{18}	

7.3 | ACTIVE SUBSTRATE MATERIALS

Active substrate materials are primarily used for sensors and actuators in a microsystem (Fig. 1.5) or other MEMS components (Fig. 1.7). Typical active substrate materials for microsystems include silicon, gallium arsenide, germanium, and quartz. We realize that all these materials except quartz are classified as semiconductors in Table 7.1. These substrate materials have basically a cubic crystal lattice with a tetrahedral atomic bond. [Sze 1985]. These materials are selected as active substrates primarily for their dimensional stability, which is relatively insensitive to environmental conditions. Dimensional stability is a critical requirement for sensors and actuators with high precision.

As indicated in the periodic table (Fig. 3.3), each atom of these semiconductor materials carries four electrons in the outer orbit. Each atom also shares these four electrons with its four neighbors. The force of attraction for electrons by both nuclei

holds each pair of shared atoms together. They can be doped with foreign materials to alter their electric conductivity as described in Section 3.5.

7.4 | SILICON AS A SUBSTRATE MATERIAL

7.4.1 The Ideal Substrate for MEMS

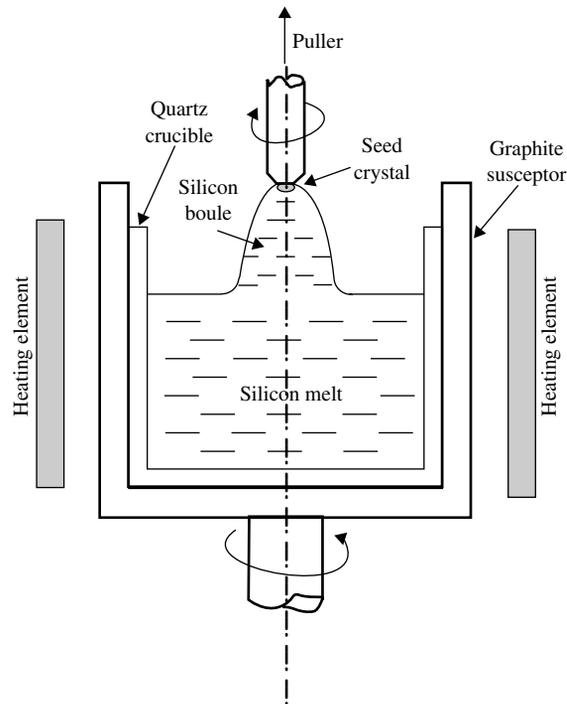
Silicon is the most abundant material on earth. However, it almost always exists in compounds with other elements. Single-crystal silicon is the most widely used substrate material for MEMS and microsystems. The popularity of silicon for such application is primarily for the following reasons:

1. It is mechanically stable and it can be integrated into electronics on the same substrate. Electronics for signal transduction, such as a p- or n-type piezoresistor, can be readily integrated with the Si substrate.
2. Silicon is almost an ideal structural material. It has about the same Young's modulus as steel (about 2×10^5 MPa), but is as light as aluminum, with a mass density of about 2.3 g/cm³. Materials with a high Young's modulus can better maintain a linear relationship between applied load and the induced deformations.
3. It has a melting point at 1400°C, which is about twice as high as that of aluminum. This high melting point makes silicon dimensionally stable even at elevated temperature.
4. Its thermal expansion coefficient is about 8 times smaller than that of steel, and is more than 10 times smaller than that of aluminum.
5. Above all, silicon shows virtually no mechanical hysteresis. It is thus an ideal candidate material for sensors and actuators. Moreover, silicon wafers are extremely flat and accept coatings and additional thin-film layers for building microstructural geometry or conducting electricity.
6. There is a greater flexibility in design and manufacture with silicon than with other substrate materials. Treatments and fabrication processes for silicon substrates are well established and documented.

7.4.2 Single-Crystal Silicon and Wafers

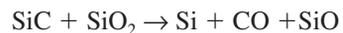
To use silicon as a substrate material, it has to be pure silicon in a single-crystal form. The Czochralski (CZ) method appears to be the most popular method among several methods that have been developed for producing pure silicon crystal. The raw silicon, in the form of quartzite are melted in a quartz crucible, with carbon (coal, coke, wood chips, etc). The crucible is placed in a high-temperature furnace as shown in Figure 7.1 [Ruska 1987]. A "seed" crystal, which is attached at the tip of a puller, is brought into contact with the molten silicon to form a larger crystal. The puller is slowly pulled up along with a continuous deposition of silicon melt onto the seed crystal. As the puller is pulled up, the deposited silicon melt condenses and a large bologna-shaped boule of single-crystal silicon several feet long is formed. Figure 7.2 shows one of such boules produced by this method. The diameter of the boules ranges from 100 mm to 300 mm.

Figure 7.1 | The Czochralski method for growing single crystals. (Ruska [1987].)



The silicon crystal boule produced by the CZ method is then ground to a perfect circle on its outside surface, then sliced to form thin disks of the desired thickness by fine diamond saws. These thin disks are then chemically-lap polished to form the finished wafers.

Principal materials in the silicon melt are silicon oxide and silicon carbide. These materials react at high temperature to produce pure silicon, along with other gaseous by-products as shown in the following chemical reaction:



The gases produced by the above reaction escape to the atmosphere and the liquid Si is left and solidifies to pure silicon. Circular pure-crystal silicon boules are produced by this technique in three standard sizes: 100 mm (4 in), 150 mm (6 in) and 200 mm (8 in) in diameters. A larger size of boule at 300 mm (12 in) in diameter is the latest addition to the standard wafer sizes. Current industry standard on wafer sizes and thicknesses are as follows:

- 100 mm (4 in) diameter \times 500 μm thick
- 150 mm (6 in) diameter \times 750 μm thick
- 200 mm (8 in) diameter \times 1 mm thick
- 300 mm (12 in) diameter \times 750 μm thick (tentative)

Figure 7.2 | A 300-mm single-crystal silicon boule cooling on a material-handling device.



(Courtesy of MEMC Electronic Materials Inc., St. Peters, Missouri.)

The size difference between a 200-mm and a 300-mm wafer is shown in Figure 7.3. The latter size wafer has 2.25 times more surface area than the 200 mm wafer and thus provides significant economic advantage for accommodating many more substrates on a single wafer.

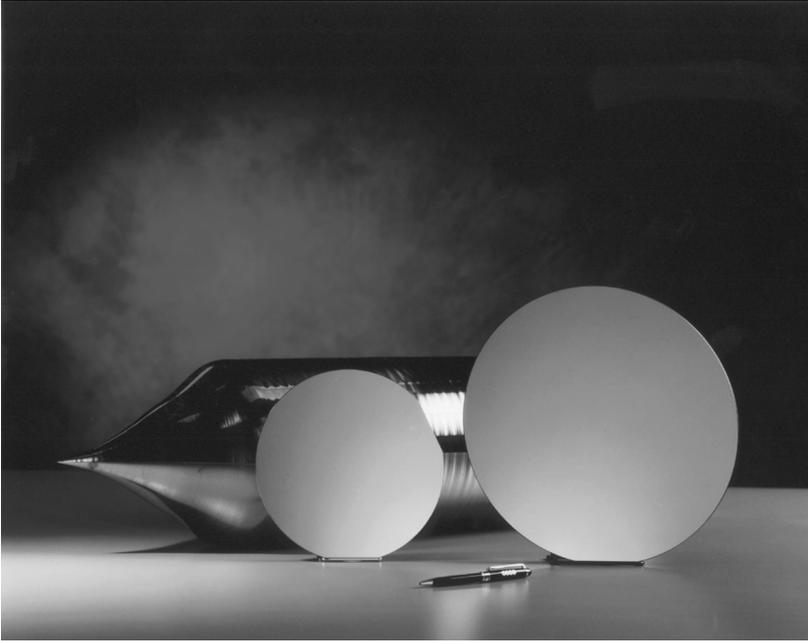
Silicon substrates often are expected to carry electric charges, either in certain designated parts or in the entire area, as in the resonant frequency pressure sensors described in Section 4.3.6. Substrates thus often require p or n doping of the wafers. The doping of p- and n-type impurities, as described in Section 3.5, can be done either by ion implantation or by diffusion, as will be described in detail in Chapter 8. Common n-type dopants of silicon are phosphorus, arsenic, and antimony, whereas boron is the most common p-type dopant for silicon.

7.4.3 Crystal Structure

Silicon has an uneven lattice geometry for its atoms, but it has basically a face-centered cubic (FCC) unit cell as illustrated in Figure 7.4. A unit cell consists of atoms situated at fixed locations defined by imaginary lines called a *lattice*. The dimension b of the lattice is called the *lattice constant* in the figure. In a typical FCC crystal, atoms are situated at the eight corners of the cubic lattice structure, as well as at the center of each of the six faces. We have shown those “visible” atoms in black and the “invisible” or “hidden” ones in gray in Figure 7.4. For silicon crystals, the

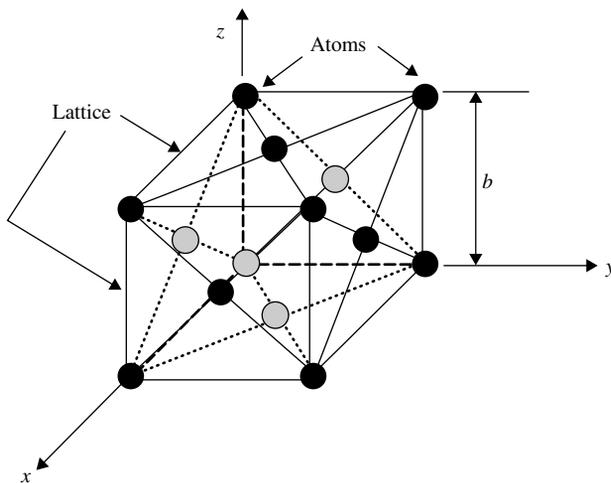
lattice constant $b = 0.543$ nm. In an FCC lattice, each atom is bonded to 12 nearest-neighbor atoms.

Figure 7.3 | Size difference between a 200-mm wafer and a 300-mm wafer.



(Courtesy of MEMC Electronic Materials Inc., St. Peters, Missouri.)

Figure 7.4 | A typical face-center-cubic unit cell.



The crystal structure of silicon, however, is more complex than that of regular FCC structure illustrated in Figure 7.4. It can be considered the result of two interpenetrating face-centered cubic crystals, FCC A and FCC B, illustrated in Figure 7.5a [Angell et al. 1983]. Consequently, the silicon crystal contains an additional four atoms as shown in Figure 7.5 b.

Figure 7.5 | Structure of a silicon crystal.

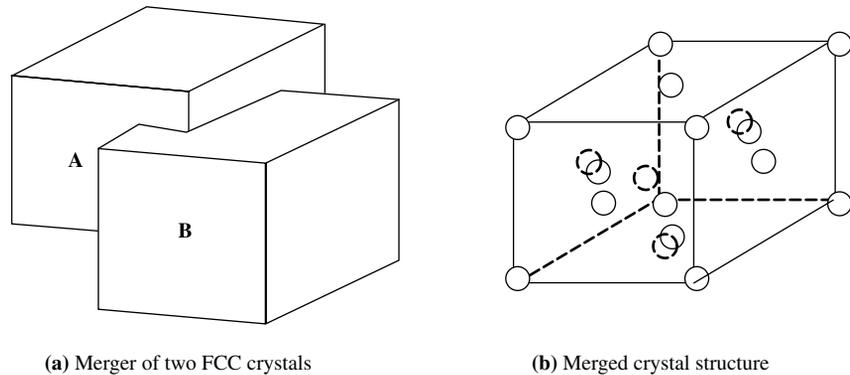
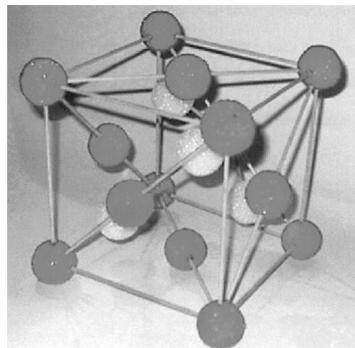


Figure 7.6 shows a three-dimensional model of the crystal structure of silicon. A closer look at this structure will reveal that these four additional atoms in the interior of the FCC (the white balls in Fig. 7.6) form a subcubic cell of the diamond lattice type as illustrated in Figure 7.7 [Ruska 1987]. A silicon unit cell thus has 18 atoms with 8 atoms at the corners plus 6 atoms on the faces and another 4 interior atoms. Many perceive the crystal structure of silicon to be a *diamond lattice* at a cubic lattice spacing of 0.543 nm [Kwok 1997].

Figure 7.6 | Photograph of a silicon crystal structure



The spacing between adjacent atoms in the diamond subcell is 0.235 nm [Brysek et al. 1991, Sze 1985, Ruska 1987]. Four equally spaced nearest-neighbor atoms that lie at the corners of a tetrahedron make the diamond lattice, as shown in the inset in

Figure 7.7 | A subcubic cell of the diamond lattice type in a silicon crystal.

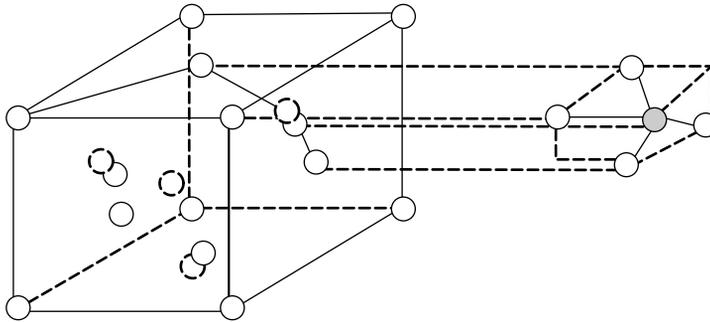


Figure 7.7. One may also perceive the silicon crystal as being stacked layers of repeating cubes. Each cube has an atom at each corner and at the center of each face (FCC structure). These cubes are interlocked with four neighboring cubes in bulk single-crystal silicon boules, and the wafers are sliced from the boules.

Because of the asymmetrical and nonuniform lattice distance between atoms, single-crystal silicon exhibits anisotropic thermophysical and mechanical characteristics that need to be understood for the benefits of handling and manufacturing. These orientation-dependent material characteristics can be better expressed by using the Miller indices [Ruska 1987, Sze 1985].

EXAMPLE 7.1

Estimate the number of atoms per cubic centimeter of pure silicon.

Solution

Since the lattice constant $b = 0.543 \text{ nm} = 0.543 \times 10^{-9} \text{ m}$, and there are 18 atoms in each cubic cell, the number of atoms in a cubic centimeter, with $1 \text{ cm} = 0.01 \text{ m}$, is

$$N = \left(\frac{V}{v}\right)n = \left(\frac{0.01}{0.543 \times 10^{-9}}\right)^3 \times 18 = 1.12 \times 10^{23} \text{ atoms/cm}^3$$

In the above computation, V and v represent respectively the bulk volume of silicon in the question and the volume of a single crystal and n is the number of atoms in a single unit crystal of silicon.

7.4.4 The Miller Indices

Because of the skew distribution of atoms in a silicon crystal, material properties are by no means uniform in the crystal. It is important to be able to designate the principal orientations as well as planes in the crystal on which the properties are specified. A popular method of designating crystal planes and orientations is the *Miller indices*. These indices are effectively used to designate planes of materials in cubic crystal families. We will briefly outline the principle of these indices as follows.

Let us consider a point $P(x, y, z)$ in an arbitrary plane in a space defined by the cartesian coordinate system x - y - z . The equation that defines the point P is

$$\frac{x}{a} + \frac{y}{b} + \frac{z}{c} = 1 \quad (7.1)$$

where a , b , and c are the intercepts formed by the plane with the respective x , y , and z axes.

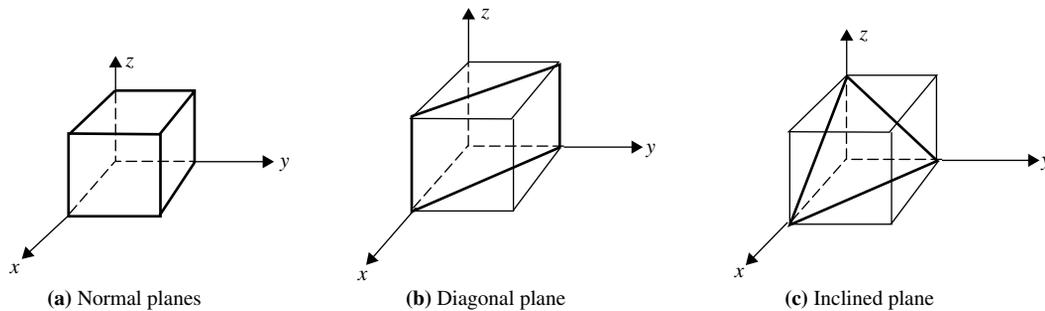
Equation (7.1) can be re-written as:

$$hx + ky + mz = 1 \quad (7.2)$$

It is apparent that $h = 1/a$, $k = 1/b$, and $m = 1/c$ in Equation (7.2).

Now, if we let (hkm) designate the plane and $\langle hkm \rangle$ designate the direction that is normal to the plane (hmk) , then we may designate the three planes that apply to a cubic crystal. These three groups of planes are illustrated in Figure 7.8. We will assume that the cubic structure has unit length with the intercepts $a = b = c = 1.0$.

Figure 7.8 | Designation of the planes of a cubic crystal.



We can designate various planes in Figure 7.8 by using Equations (7.1) and (7.2) as follows:

Top face in Figure 7.8a:	(001)
Right face in Figure 7.8a:	(010)
Front face in Figure 7.8a:	(100)
Diagonal face in Figure 7.8b:	(110)
Inclined face in Figure 7.8c:	(111)

The orientations of these planes can be represented by $\langle 100 \rangle$, which is perpendicular to plane (100), $\langle 111 \rangle$, which is normal to the plane (111), etc. Figure 7.9 shows these three planes and orientations for a unit cell in single-crystal silicon.

The silicon atoms in the three principal planes, (100), (110) and (111), are illustrated in Figure 7.10. The atoms shown in open circles are those at the corners of the cubic, solid circles in gray are the ones at the center of the faces, and the gray circles in dotted lines are the atoms at the interior of the unit cell.

As shown in Figures 7.6 and 7.10, the lattice distances between adjacent atoms are shortest for those atoms on the (111) plane. These short lattice distances between

Figure 7.9 | Silicon crystal structure and planes and orientations.

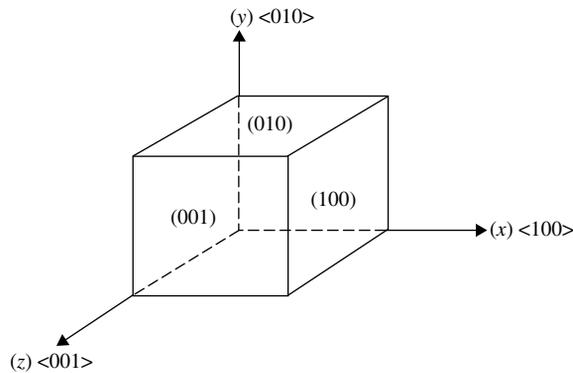
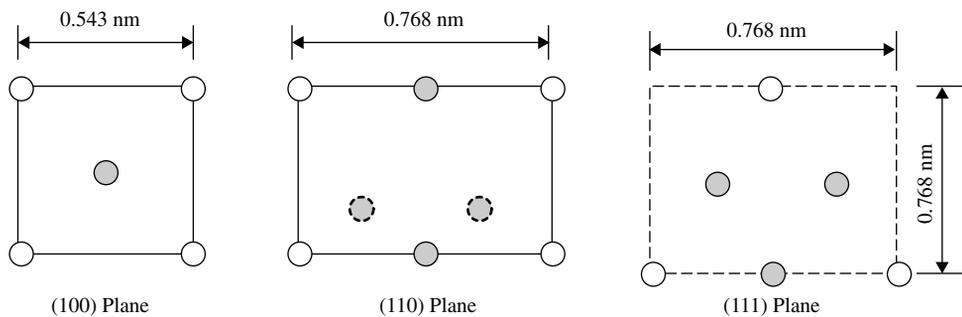
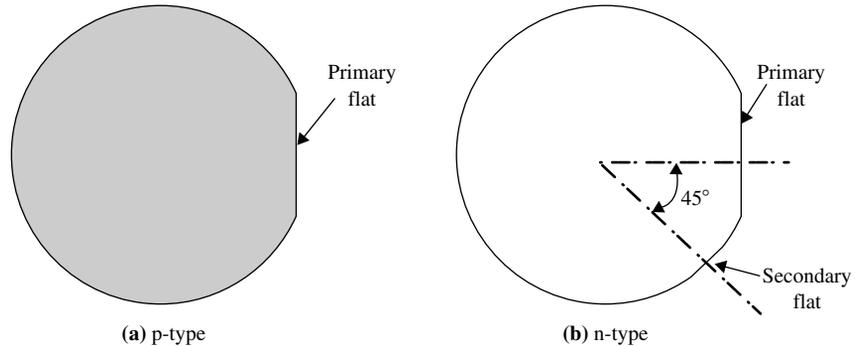


Figure 7.10 | Silicon atoms on three designated planes.



atoms make the attractive forces between atoms stronger on this plane than those on the other two planes. Also, this plane contains three of the four atoms that are situated at the center of the faces of the unit cell (in gray). Thus, the growth of crystal in this plane is the slowest and the fabrication processes, e.g., etching, as we will learn in Chapters 8 and 9, will proceed slowest.

Because of the importance of the orientation-dependent machinability of silicon substrates, wafers that are shipped by suppliers normally indicate in which directions, i.e., $\langle 110 \rangle$, $\langle 100 \rangle$, or $\langle 111 \rangle$ the cuts have been made, by “flats” as illustrated in Figure 7.11. The edge of silicon crystal boules can be ground to produce single *primary flats*, and in some cases, with additional single *secondary flats*. The wafers that are sliced from these crystal boules may thus contain one or two flats as shown in Figure 7.11. The primary flats are used to indicate the crystal orientation of the wafer structure, whereas the secondary flats are used to indicate the dopant type of the wafer. For example, Figure 7.11a indicates a flat that is normal to the $\langle 111 \rangle$ orientation with p-type of silicon crystal. The wafer with additional second flat at 45° from the primary flat in Figure 7.11b indicates an n-type doping in the wafer. Other arrangements of flats in wafers for various designations can be found in [van Zant 1997, Madou 1997].

Figure 7.11 | Primary and secondary flats in silicon wafers.

7.4.5 Mechanical Properties of Silicon

Silicon is mainly used as an integrated circuit carrier in microelectronics. For microsystems, it is the prime candidate material for sensors and actuators, as well as common substrates for microfluidics. The technology that is used in implementing the IC on silicon dies is used in a similar way for microsystems. However, silicon, as the material of components of generally three-dimensional geometry, needs to withstand often-severe mechanical and thermal loads, in addition to accommodating electrical instruments such as piezoresistive integrated into it. It is thus important to have a good understanding of the mechanical characteristics of silicon as a structural material.

Basically, silicon is an elastic material with no plasticity or creep below 800°C. It shows virtually no fatigue failure under all conceivable circumstances. These unique characteristics make it an ideal material for sensing and actuating in microsystems. However, it is a brittle material. Therefore, undesirable brittle fracture behavior with weak resistance to impact loads needs to be considered in the design of such microsystems. Another disadvantage of silicon substrates is that they are anisotropic. This makes accurate stress analysis of silicon structures tedious, since directional mechanical property must be included. For example, Table 7.2 indicates the different Young's modulus and shear modulus of elasticity of silicon crystals in different orientations [Madou 1997]. For most cases in microsystem design, the bulk material properties of silicon, silicon compounds, and other active substrate materials presented in Table 7.3 are used.

Table 7.2 | The diverse Young's moduli and shear moduli of elasticity of silicon crystals

Miller index for orientation	Young's modulus E , GPa	Shear modulus G , GPa
$\langle 100 \rangle$	129.5	79.0
$\langle 110 \rangle$	168.0	61.7
$\langle 111 \rangle$	186.5	57.5

Table 7.3 | Mechanical and thermophysical properties of MEMS materials*

Material	σ_y , 10 ⁹ N/m ²	E , 10 ¹¹ N/m ²	ρ , g/cm ³	c , J/g·°C	k , W/cm·°C	α , 10 ⁻⁶ /°C	T_M , °C
Si	7.00	1.90	2.30	0.70	1.57	2.33	1400
SiC	21.00	7.00	3.20	0.67	3.50	3.30	2300
Si ₃ N ₄	14.00	3.85	3.10	0.69	0.19	0.80	1930
SiO ₂	8.40	0.73	2.27	1.00	0.014	0.50	1700
Aluminum	0.17	0.70	2.70	0.942	2.36	25	660
Stainless steel	2.10	2.00	7.90	0.47	0.329	17.30	1500
Copper	0.07	0.11	8.9	0.386	3.93	16.56	1080
GaAs	2.70	0.75	5.30	0.35	0.50	6.86	1238
Ge		1.03	5.32	0.31	0.60	5.80	937
Quartz	0.5-0.7	0.76-0.97	2.66	0.82-1.20	0.067-0.12	7.10	1710

*Principal source for semiconductor material properties: *Fundamentals of Microfabrication*, Marc Madou, CRC Press, 1997

Legend: σ_y = yield strength, E = Young's modulus, ρ = mass density, c = specific heat, k = thermal conductivity, α = coefficient of thermal expansion, T_M = melting point.

EXAMPLE 7.2

As indicated in Chapter 5, the thermal diffusivity of a material is a measure of how fast heat can flow in the material. List the thermal diffusivities of silicon, silicon dioxide, aluminum, and copper, and make an observation on the results.

Solution

The thermal diffusivity α is a function of several properties of the material as shown in Equation (5.39):

$$\alpha = \frac{k}{\rho c}$$

where the properties k , ρ , and c for the four materials are given in Table 7.3. They are listed in slightly different units in Table 7.4.

Table 7.4 | Thermal diffusivity of selected materials for microsystems

Material	k , J/sce-m·°C	ρ , g/m ³	c , J/g·°C	Thermal diffusivity, α , m ² /s
Si	157	2.3 × 10 ⁶	0.7	97.52 × 10 ⁻⁶
SiO ₂	1.4	2.27 × 10 ⁶	1.0	0.62 × 10 ⁻⁶
Aluminum	236	2.7 × 10 ⁶	0.94	93 × 10 ⁻⁶
Copper	393	8.9 × 10 ⁶	0.386	114.4 × 10 ⁻⁶

By substituting the material properties tabulated in the three left columns in Table 7.4 into Equation (5.39), we can compute the thermal diffusivities of the materials as indicated in the right column in the same table. It is not surprising to observe that copper has the highest thermal diffusivity, whereas silicon and aluminum have about the same value. Useful information from this exercise is that silicon oxide conducts heat more than 150 times slower than silicon and aluminum.

We may thus conclude that copper films are the best material for fast heat transmission in microsystems, whereas silicon dioxide can be used as an effective thermal barrier.

7.5 | SILICON COMPOUNDS

Three silicon compounds are often used in microsystems: silicon dioxide, SiO₂; silicon carbide, SiC; and silicon nitride, Si₃N₄. We will take a brief look at each of these compounds as to the roles they play in microsystems.

7.5.1 Silicon Dioxide

There are three principal uses of silicon oxide in microsystems: (1) as a thermal and electric insulator (see Table 7.1 for the low electric resistivity of oxides), (2) as a mask in the etching of silicon substrates, and (3) as a sacrificial layer in surface micromachining, as will be described in Chapter 9. Silicon oxide has much stronger resistance to most etchants than silicon. Important properties of silicon oxide are listed in Table 7.5.

Table 7.5 | Properties of silicon dioxide

Properties	Values
Density, g/cm ³	2.27
Resistivity, Ω-cm	≥10 ¹⁶
Relative permittivity	3.9
Melting point, °C	~1700
Specific heat, J/g-°C	1.0
Thermal conductivity, W/cm-°C	0.014
Coefficient of thermal expansion, ppm/°C	0.5

Source: Ruska [1987].

Silicon dioxide can be produced by heating silicon in an oxidant such as oxygen with or without steam. Chemical reactions for such processes are:



for “dry” oxidation, and



for “wet” oxidation in steam.

Oxidation is effectively a diffusion process, as described in Chapter 3. Therefore, the rate of oxidation can be controlled by similar techniques used for most other diffusion processes. Typical diffusivity of silicon dioxide at 900°C in dry oxidation is 4×10^{-19} cm²/s for arsenic-doped (n-type) silicon and 3×10^{-19} cm²/s for boron-doped (p-type) silicon [Sze 1985]. The process can be accelerated to much faster

rates by the presence of steam; the highly activated H_2O molecules enhance the process. As in all diffusion processes, the diffusivity of the substance to be diffused into the base material is the key parameter for the effectiveness of the diffusion process.

7.5.2 Silicon Carbide

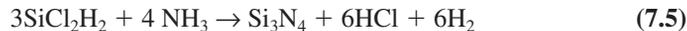
The principal application of silicon carbide (SiC) in microsystems is its dimensional and chemical stability at high temperatures. It has very strong resistance to oxidation even at very high temperatures. Thin films of silicon carbide are often deposited over MEMS components to protect them from extreme temperature. Another attraction of using SiC in MEMS is that dry etching (to be described in Chapters 8 and 9) with aluminum masks can easily pattern the thin SiC film. The patterned SiC film can further be used as a passivation layer (protective layer) in micromachining for the underlying silicon substrate, as SiC can resist common etchants such as KOH and HF.

Silicon carbide is a by-product in the process of producing single crystal silicon boules as described in Section 7.4.2. As silicon exists in the raw materials of carbon (coal, coke, wood chips, etc.), the intense heating of these materials in the electric arc furnace results in SiC sinking to the bottom of the crucible. Silicon carbide films can be produced by various deposition techniques. Pertinent thermophysical properties of SiC are given in Table 7.3.

7.5.3 Silicon Nitride

Silicon nitride (Si_3N_4) has many superior properties that are attractive for MEMS and microsystems. It provides an excellent barrier to diffusion of water and ions such as sodium. Its ultrastrong resistance to oxidation and many etchants makes it suitable for masks for deep etching. Applications of silicon nitride include optical waveguides, encapsulants to prevent diffusion of water and other toxic fluids into the substrate. It is also used as high-strength electric insulators and ion implantation masks.

Silicon nitride can be produced from silicon-containing gases and NH_3 in the following reaction:



Selected properties of silicon nitride are listed in Table 7.6. Both chemical vapor deposition processes [*low-pressure chemical vapor deposition* (LPCVD) and the *plasma-enhanced chemical vapor deposition* (PECVD)] in Table 7.6 will be described in detail in Chapter 8. Additional material properties are given in Table 7.3.

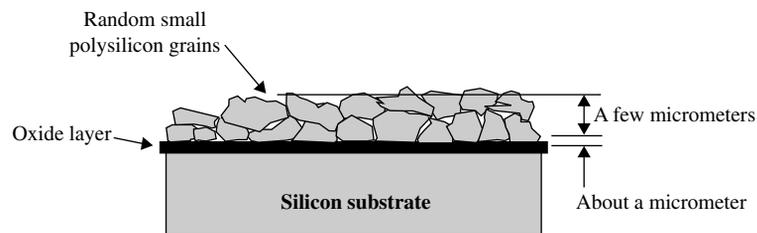
7.5.4 Polycrystalline Silicon

Silicon in polycrystalline form can be deposited onto silicon substrates by chemical vapor deposition (CVD) as illustrated in Figure 7.12. It has become a principal material in surface micromachining, as will be described in Chapter 9.

Table 7.6 | Selected properties of silicon nitride

Properties	LPCVD	PECVD
Deposition temperature, °C	700–800	250–350
Density, g/cm ³	2.9–3.2	2.4–2.8
Film quality	Excellent	Poor
Relative permittivity	6–7	6–9
Resistivity, Ω-cm	10 ¹⁶	10 ⁶ –10 ¹⁵
Refractive index	2.01	1.8–2.5
Atom % H	4–8	20–25
Etch rate in concentrated HF	200 Å/min	
Etch rate in boiling HF	5–10 Å/min	
Poisson's ratio	0.27	
Young's modulus, GPa	385	
Coefficient of thermal expansion, ppm/°C	1.6	

Source: Madou [1997].

Figure 7.12 | Polysilicon deposits on a silicon substrate.

The low pressure chemical vapor deposition (LPCVD) process is frequently used for depositing polycrystalline silicon onto silicon substrates. The temperature involved in this process is about 600 to 650°C. Polysilicon (an abbreviation of polycrystalline silicon) is widely used in the IC industry for resistors, gates for transistors, thin-film transistors, etc. Highly doped polysilicon, (with arsenic and phosphorous for n type or boron for p type) can drastically reduce the resistivity of polysilicon to produce conductors and control switches. They are thus ideal materials for micro-resistors as well as easy ohmic contacts. A comparison of some key properties of polysilicon and other materials is presented in Table 7.7. Being a congregation of single silicon crystals in random sizes and orientations, polysilicon can be treated as isotropic material in thermal and structural analyses.

7.6 | SILICON PIEZORESISTORS

Piezoresistance is defined as a change in electrical resistance of solids when subjected to stress fields. Silicon piezoresistors that have such characteristics are widely used in microsensors and actuators.

We have learned from Chapter 3 and Section 7.4.2 that doping boron into the silicon lattice produces p-type silicon crystal while doping arsenic or phosphorus

Table 7.7 | Comparison of mechanical properties of polysilicon and other materials

Materials	Young's modulus, GPa	Poisson's ratio	Coefficient of thermal expansion, ppm/°C
<i>As substrates:</i>			
Silicon	190	0.23	2.6
Alumina	415		8.7
Silica	73	0.17	0.4
<i>As thin films:</i>			
Polysilicon	160	0.23	2.8
Thermal SiO ₂	70	0.2	0.35
LPCVD SiO ₂	270	0.27	1.6
PECVD SiO ₂			2.3
Aluminum	70	0.35	25
Tungsten	410	0.28	4.3
Polymide	3.2	0.42	20–70

Source: Madou [1997].

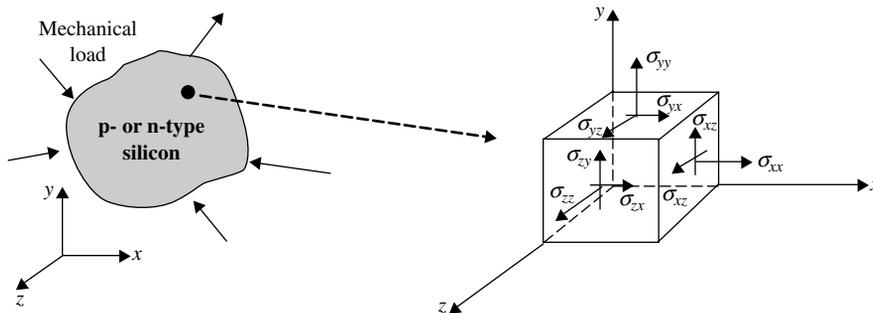
results in n-type silicon. Both p- and n-type silicon exhibit excellent piezoresistive effect. Charles Smith in 1954 discovered the piezoresistance of p- and n-type silicon.

The fact that silicon crystal, whether it is p type or n type, is anisotropic has made the relationship between the change of resistance and the existent stress field more complex. This relationship is shown below:

$$\{\Delta R\} = [\pi]\{\sigma\} \tag{7.6}$$

where $\{\Delta R\} = \{\Delta R_{xx} \ \Delta R_{yy} \ \Delta R_{zz} \ \Delta R_{xy} \ \Delta R_{xz} \ \Delta R_{yz}\}^T$ represents the change of resistance in an infinitesimally small cubic piezoresistive crystal element with corresponding stress components $\{\sigma\} = \{\sigma_{xx} \ \sigma_{yy} \ \sigma_{zz} \ \sigma_{xy} \ \sigma_{xz} \ \sigma_{yz}\}^T$ as shown in Figure 7.13. Of the six independent stress components in the stress tensor $\{\sigma\}$, there are three normal stress components, σ_{xx} , σ_{yy} , and σ_{zz} , and three shearing stress components, σ_{xy} , σ_{xz} , and σ_{yz} . The vector $[\pi]$ in Equation (7.6) is referred to as *piezoresistive coefficient matrix*. It has the following form:

Figure 7.13 | A silicon piezoresistance subjected to a stress field.



$$[\pi] = \begin{bmatrix} \pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \pi_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \pi_{44} \end{bmatrix} \quad (7.7)$$

We notice from Equation (7.7) that only three coefficients, π_{11} , π_{12} , and π_{44} , appear in the matrix. By expanding the matrix equation in Equation (7.6) with the appropriate piezoresistive coefficients in Equation (7.7), we will have the following relations:

$$\Delta R_{xx} = \pi_{11}\sigma_{xx} + \pi_{12}(\sigma_{yy} + \sigma_{zz})$$

$$\Delta R_{yy} = \pi_{11}\sigma_{yy} + \pi_{12}(\sigma_{xx} + \sigma_{zz})$$

$$\Delta R_{zz} = \pi_{11}\sigma_{zz} + \pi_{12}(\sigma_{xx} + \sigma_{yy})$$

$$\Delta R_{xy} = \pi_{44}\sigma_{xy}$$

$$\Delta R_{xz} = \pi_{44}\sigma_{xz}$$

$$\Delta R_{yz} = \pi_{44}\sigma_{yz}$$

It is thus apparent that the coefficients π_{11} and π_{12} are associated with the normal stress components, whereas the coefficient π_{44} is related to the shearing stress components.

The actual values of these three coefficients depend on the angles of the piezoresistor with respect to the silicon crystal lattice. The values of these coefficients at room temperature are given in Table 7.8.

Table 7.8 | Resistivity and piezoresistive coefficients of silicon at room temperature in $\langle 100 \rangle$ orientation

Materials	Resistivity, $\Omega\text{-cm}$	π_{11}^*	π_{12}^*	π_{44}^*
p silicon	7.8	+6.6	-1.1	+138.1
n silicon	11.7	-102.2	+53.4	-13.6

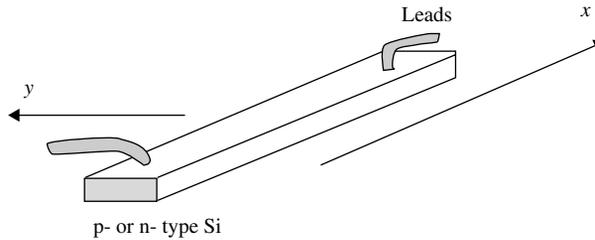
*in $10^{-12}\text{cm}^2/\text{dyne}$ or in $10^{-11}\text{m}^2/\text{N}$ (or Pa^{-1})

Source: French and Evans [1988].

Equation (7.6) and the situation illustrated in Figure 7.13, of course, represent general cases of piezoresistive crystals in a three-dimensional geometry. In almost all applications in MEMS and microsystems, silicon piezoresistors exist in the form of thin strips such as illustrated in Figure 7.14. In such cases, only the in-plane stresses in the x and y directions need to be accounted for.

We will realize from Table 7.8 that the maximum piezoresistive coefficient for p-type silicon is $\pi_{44} = +138.1 \times 10^{-11} \text{ Pa}^{-1}$, and the maximum coefficient for the n-type silicon is $\pi_{11} = -102.2 \times 10^{-11} \text{ Pa}^{-1}$. Thus, many silicon piezoresistors are made of p-type material with boron as the dopant. Table 7.9 presents the values of piezoresistive coefficients for the p-type silicon piezoresistors made in various crystal planes [Brysek et al. 1991].

Figure 7.14 | Silicon strain gages.



The values of π_L denote the piezoresistive coefficient along the longitudinal direction, i.e., along the $\langle x \rangle$ direction in Figure 7.14, whereas π_T represents the piezoresistive coefficient in the tangential direction, i.e., along the $\langle y \rangle$ direction in the same figure.

Table 7.9 | Piezoresistive coefficients of p-type silicon piezoresistors in various directions

Crystal planes	Orientation $\langle x \rangle$	Orientation $\langle y \rangle$	π_L	π_T
(100)	$\langle 111 \rangle$	$\langle 211 \rangle$	$+0.66\pi_{44}$	$-0.33\pi_{44}$
(100)	$\langle 110 \rangle$	$\langle 100 \rangle$	$+0.5\pi_{44}$	~ 0
(100)	$\langle 110 \rangle$	$\langle 110 \rangle$	$+0.5\pi_{44}$	$-0.5\pi_{44}$
(100)	$\langle 100 \rangle$	$\langle 100 \rangle$	$+0.02\pi_{44}$	$+0.02\pi_{44}$

Source: Brysek et al. [1991].

The change of electric resistance in a silicon piezoresistance gage can thus be expressed as:

$$\frac{\Delta R}{R} = \pi_L \sigma_L + \pi_T \sigma_T \tag{7.8}$$

in which ΔR and R are respectively the change of resistance and the original resistance of the silicon piezoresistive. The value of the original resistance R in Equation (7.8) can be obtained either by direct measurement, or by using the formula $R = \frac{\rho L}{A}$ in which ρ is the resistivity of the piezoresistor such as given in Figure 3.8, L and A are respective length and cross-sectional area of the piezoresistor. The piezoresistive coefficients in both longitudinal and tangential directions are given in Table 7.9 for p-type silicon piezoresistives. The stress components in the longitudinal and tangential directions, σ_L and σ_T , are the stresses that cause the change of the resistance in the piezoresistor.

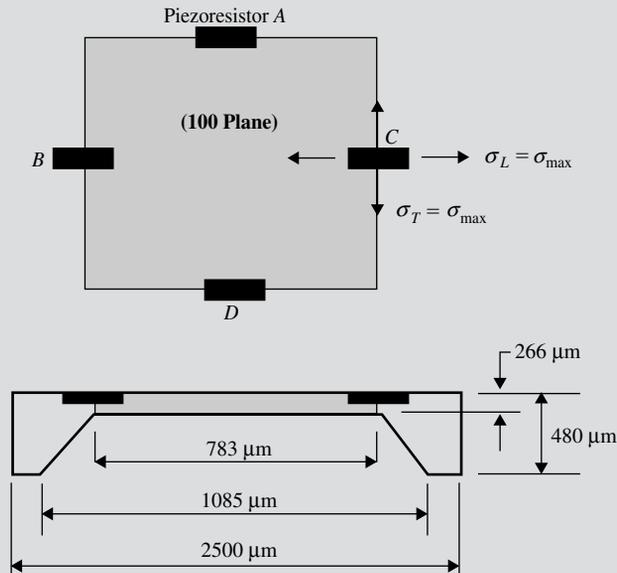
EXAMPLE 7.3

Estimate the change of resistance in piezoresistors attached to the diaphragm of a pressure sensor described in Example 4.4 in Chapter 4.

Solution

Let us reillustrate the situation in Example 4.4 in Figure 7.15. There are four identical piezoresistors, *A*, *B*, *C*, and *D*, diffused in the locations at the top face of the silicon die as shown in the figure. Resistors *A* and *D* are subjected predominantly to the transverse stress component σ_T that is normal to the horizontal edges, whereas resistors *B* and *C* are subjected to the longitudinal stress σ_L that is normal to the vertical edges.

Figure 7.15 | Piezoresistors in a pressure sensor die.



Because of the square plane geometry of the diaphragm that is subjected to uniform pressure loading at the top surface, the bending moments normal to all edges are equal in magnitudes. Thus, we may let $\sigma_L = \sigma_T = \sigma_{\max} = 186.8 \text{ MPa} = 186.8 \times 10^6 \text{ Pa}$ (from Example 4.4).

We assume that the diaphragm is on the (100) plane and both stresses are along the $\langle 100 \rangle$ directions (why?), we thus obtain the piezoresistive coefficient $\pi_L = \pi_T = 0.02\pi_{44}$ from Table 7.9 for p-type piezoresistors. The value of the piezoresistive coefficient π_{44} is available from Table 7.8; it is $\pi_{44} = 138.1 \times 10^{-11} \text{ Pa}^{-1}$.

We can thus estimate the change of electric resistance in the piezoresistors to be:

$$\begin{aligned} \frac{\Delta R}{R} &= \pi_L \sigma_L + \pi_T \sigma_T = 2 \times 0.02\pi_{44} \sigma_{\max} = 2 \times 0.02(138.1 \times 10^{-11})(186.8 \times 10^6) \\ &= 0.01032\Omega/\Omega \end{aligned}$$

Determining the net change of resistance in the resistors requires knowledge of the length of the resistor in the stress-free state and the resistivity of the resistor material as given in Figure 3.8.

One major drawback of silicon piezoresistors is the strong temperature dependence of their piezoresistivity. The sensitivity of piezoresistivity to the applied stress deteriorates rapidly with increase of temperature. Table 7.10 presents the variation of piezoresistive coefficients with reference to those at room temperature.

Table 7.10 | Temperature dependence of resistivity and piezoresistivity of silicon piezoresistors

Doping concentration, $10^{19}/\text{cm}^3$	p-type TCR, % per °C	p-type TCP, % per °C	n-type TCR, % per °C	n-type TCP, % per °C
5	0.0	-0.27	0.01	-0.28
10	0.01	-0.27	0.05	-0.27
30	0.06	-0.18	0.09	-0.18
100	0.17	-0.16	0.19	-0.12

Source: [French and Evans 1988].

TCR = temperature coefficient of resistance; TCP = temperature coefficient of piezoresistivity.

Take for example, a p-type silicon piezoresistor with a doping concentration of 10^{19} per cm^3 ; the loss of piezoresistivity is 0.27% per °C. The same piezoresistor operating at 120°C would have lost $(120 - 20) \times 0.27\% = 27\%$ of the value of the piezoresistivity coefficient. Appropriate compensation for this loss must be considered in the design of signal conditioning systems.

The doping concentration for piezoresistives normally should be kept below $10^{19}/\text{cm}^3$ because the piezoresistive coefficients drop considerably above this dose, and reverse breakdown becomes an issue.

7.7 | GALLIUM ARSENIDE

Gallium arsenide (GaAs) is a compound semiconductor. It is made of equal numbers of gallium and arsenic atoms. Because it is a compound, it is more complicated in lattice structure, with atoms of both constituents, and hence is more difficult to process than silicon. However, GaAs is an excellent material for monolithic integration of electronic and photonic devices on a single substrate. The main reason that GaAs is a prime candidate material for photonic devices is its high mobility of electrons in comparison to other semiconducting materials, as shown in Table 7.11.

As we see from the table, GaAs has about 7 times higher electron mobility than silicon. The high electron mobility in this material means it is easier for electric current to flow in the material. The photoelectric effect, as illustrated in Section 2.2.4 in Chapter 2, describes the electric current flow in a photoelectric material when it is energized by incoming photons. GaAs, being a material with high mobility of

Table 7.11 | Electron mobility of selected materials at 300 K

Materials	Electron mobility, m ² /V-s
Aluminum	0.00435
Copper	0.00136
Silicon	0.145
Gallium arsenide	0.850
Silicon oxide	~0
Silicon nitride	~0

Source: Kwok [1997].

electrons, thus can better facilitate the electric current flow when it is energized by photon sources.

Gallium arsenide is also a superior thermal insulator, with excellent dimensional stability at high temperature. The negative aspect of this material is its low yield strength as indicated in Table 7.3. Its yield strength, at 2700 MPa, is only one-third of that of silicon. This makes GaAs less attractive for use as substrates in microsystems. Because of its relatively low use in the microelectronics industry, GaAs is much more expensive than silicon.

In addition to the differences in thermophysical properties as indicated in Table 7.3, Table 7.12 gives a good comparison of these two substrate materials used in microsystems.

Table 7.12 | A comparison of GaAs and silicon in micromachining

Properties	GaAs	Silicon
Optoelectronics	Very good	Not good
Piezoelectric effect	Yes	No
Piezoelectric coefficient, pN/°C	2.6	Nil
Thermal conductivity	Relatively low	Relatively high
Cost	High	Low
Bonding to other substrates	Difficult	Relatively easy
Fracture	Brittle, fragile	Brittle, strong
Operating temperature	High	Low
Optimum operating temp., °C	460	300
Physical stability	Fair	Very good
Hardness, GPa	7	10
Fracture strength, GPa	2.7	6

Source: Madou [1997].

7.8 | QUARTZ

Quartz is a compound of SiO₂. The single-unit cell for quartz is in the shape of tetrahedron with three oxygen atoms at the apexes at the base and one silicon atom at the other apex of the tetrahedron. The axis that is normal to the base plane is called the Z axis. The quartz crystal structure is made up of rings with six silicon atoms.

Quartz is close to being an ideal material for sensors because of its near absolute thermal dimensional stability. It is used in many piezoelectric devices in the market,

as will be described in Section 7.9. Commercial applications of quartz crystals include wristwatches, electronic filters, and resonators. Quartz is a desirable material in microfluidics applications in biomedical analyses. It is inexpensive and it works well in electrophoretic fluid transportation as described in Chapters 3 and 5 because of its excellent electric insulation properties. It is transparent to ultraviolet light, which often is used to detect the various species in the fluid.

Quartz is a material that is hard to machine. Diamond cutting is a common method, although ultrasonic cutting has been used for more precise geometric trimming. It can be etched chemically by HF/NH₄F into the desired shape. Quartz wafers up to 75 mm in diameter by 100 μm thick are available commercially.

Quartz is even more dimensionally stable than silicon, especially at high temperatures. It offers more flexibility in geometry than silicon despite the difficulty in machining. Some key properties are presented in Table 7.13.

Table 7.13 | Some properties of quartz

Properties	Value Z	Value ⊥ Z	Temperature dependency
Thermal conductivity, cal/cm-s ² /C	29×10^{-3}	16×10^{-3}	↓ with T
Relative permittivity	4.6	4.5	↓ with T
Density, kg/m ³	2.66×10^3	2.66×10^3	
Coefficient of thermal expansion, ppm/°C	7.1	13.2	↑ with T
Electrical resistivity, Ω/cm	0.1×10^{15}	20×10^{15}	↓ with T
Fracture strength, GPa	1.7	1.7	↓ with T
Hardness, GPa	12	12	

Source: Madou [1997].

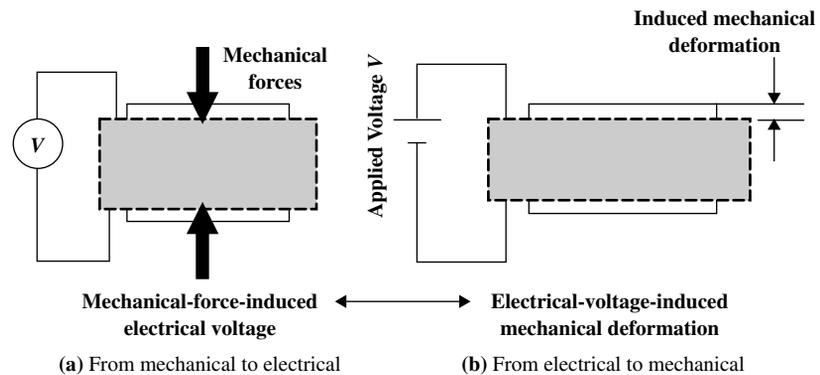
7.9 | PIEZOELECTRIC CRYSTALS

One of the most commonly used nonsemiconducting materials in MEMS and microsystems is piezoelectric crystals. Piezoelectric crystals are the solids of ceramic compounds that can produce a voltage when a mechanical force is applied between their faces. The reverse situation, that is the application of voltage to the crystal, can also change its shape. This conversion of mechanical energy to electronic signals (i.e., voltage) and vice versa is illustrated in Figure 7.16. This unique material behavior is called the *piezoelectric effect*. Jacques and Pierre Curie discovered the piezoelectric effect in 1880. This effect exists in a number of natural crystals such as quartz, tourmaline, and sodium potassium tartrate, and quartz has been used in electromechanical transducers for many years. There are many other synthesized crystals such as Rochelle salt (Na₂KC₄H₄O₆·4H₂O), barium titanate (BaTiO₃), and lead zirconate titanate (PZT).

For a crystal to exhibit the piezoelectric effect, its structure should have no center of symmetry. A stress applied to such a crystal will alter the separation between the positive and negative charge sites in each elementary cell, leading to a net polarization at the crystal surface [Waanders 1991]. An electric field with voltage potential is thus created in the crystal because of such polarization.

The most common use of the piezoelectric effect is for high voltage generation through the application of high compressive stress. The generated high-voltage field can be used as an impact detonation device. It can also be used to send signals for depth detection in a sonar system. The principal applications of the piezoelectric effect in MEMS and microsystems, however, are in actuators, as described in Chapter 2, and dynamic signal transducers for pressure sensors and accelerometers. The piezoelectric effect is also used in pumping mechanisms, as described in Chapters 5 and 6, for microfluidic flows, as well as for inkjet printer heads.

Figure 7.16 | Conversion of mechanical and electrical energies by piezoelectric crystals.



(From Kasap [1997].)

The effectiveness of the conversion of mechanical to electrical energy and vice versa can be assessed by the electromechanical conversion factor K , defined as follows [Kasop 1997]:

$$K^2 = \frac{\text{output of mechanical energy}}{\text{input of electrical energy}} \quad (7.9a)$$

or

$$K^2 = \frac{\text{output of electrical energy}}{\text{input of mechanical energy}} \quad (7.9b)$$

The following simple mathematical relationships between the electromechanical effects can be used in the design of piezoelectric transducers in unidirectional loading situations [Askeland 1994]:

1. The electric field produced by stress:

$$V = f\sigma \quad (7.10)$$

where V is the generated electric field in V/m and σ is the applied stress in pascals (Pa). The coefficient f is a constant.

2. The mechanical strain produced by the electric field:

$$\varepsilon = dV \tag{7.11}$$

in which ε is the induced strain and V is the applied electric field in V/m.

The piezoelectric coefficient d for common piezoelectric crystals is given in Table 7.14.

The coefficients f and d in Equations (7.10) and (7.11) have the following relationship:

$$\frac{1}{fd} = E \tag{7.12}$$

where E is the Young’s modulus of the piezoelectric crystal.

Table 7.14 | Piezoelectric coefficients of selected materials

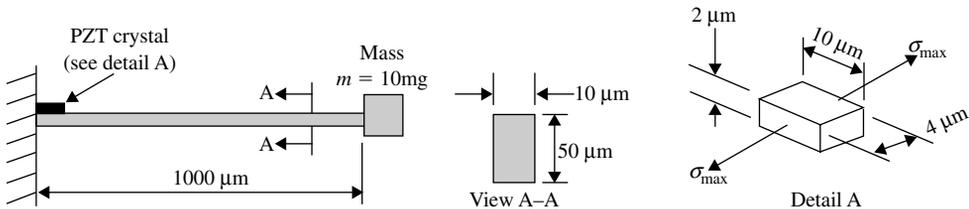
Piezoelectric crystals	Coefficient d , 10^{-12} m/V	Electromechanical conversion factor K
Quartz (crystal SiO_2)	2.3	0.1
Barium titanate (BaTiO_3)	100–190	0.49
Lead zirconate titanate, PZT ($\text{PbTi}_{1-x}\text{Zr}_x\text{O}_3$)	480	0.72
PbZrTiO_6	250	
PbNb_2O_6	80	
Rochelle salt ($\text{NaKC}_4\text{H}_4\text{O}_6 \cdot 4\text{H}_2\text{O}$)	350	0.78
Polyvinylidene fluoride, PVDF	18	

Source: Kasap [1997], Askeland [1994].

EXAMPLE 7.4

A thin piezoelectric crystal film of PZT is used to transduce the signal in a micro-accelerometer with a cantilever beam made of silicon as described in Example 4.7. The accelerometer is designed for maximum acceleration/deceleration of $10g$. The PZT transducer is located at the support base of the cantilever beam where the maximum strain exists during the bending of the beam, as illustrated in Figure 7.17. Determine the electrical voltage output from the PZT film at the maximum acceleration/deceleration of $10g$.

Figure 7.17 | Piezoelectric transducer in a beam-accelerometer.



Solution

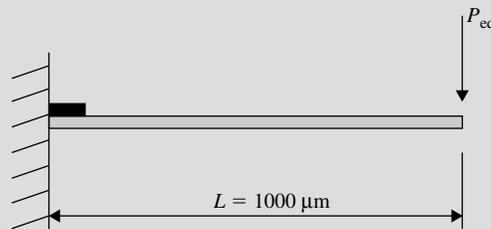
The solution can be obtained by determining the maximum bending stress, and thus the maximum bending strain in the beam due to the dynamic load of the attached mass accelerated to $10g$. The maximum bending strain in the beam is assumed to give the same magnitude of strain to the attached thin PZT film. The voltage generated in the PZT can be computed from Equation (7.11).

We will first determine the equivalent bending load P_{eq} that is equivalent to that of the 10-mg mass accelerated or decelerated to $10g$:

$$P_{eq} = ma = (10 \times 10^{-6}) \times (10 \times 9.81) = 981 \times 10^{-6} \text{ N}$$

The beam-accelerometer is equivalent to a statically loaded cantilever beam subjected to the equivalent force acting at its free end as illustrated in Figure 7.18.

Figure 7.18 | Equivalent static bending of a cantilever beam in an accelerometer.



The maximum bending moment $M_{max} = P_{eq}L = (981 \times 10^{-6})(1000 \times 10^{-6}) = 0.981 \times 10^{-6} \text{ N}\cdot\text{m}$.

We will need the moment of inertia I of the beam cross section to calculate the equivalent maximum bending stress σ_{max} . The value of I was computed in Example 4.7 to be $0.1042 \times 10^{-18} \text{ m}^4$. We thus have the maximum bending stress at the support as:

$$\sigma_{max} = \frac{M_{max} C}{I} = \frac{(0.981 \times 10^{-6})(25 \times 10^{-6})}{(0.1042 \times 10^{-18})} = 235.36 \times 10^6 \text{ Pa}$$

where C is the half-depth of the beam cross section.

The associated maximum bending strain ϵ_{max} in the beam is:

$$\epsilon_{max} = \frac{\sigma_{max}}{E} = \frac{235.36 \times 10^6}{1.9 \times 10^{11}} = 123.87 \times 10^{-5} \text{ m/m}$$

We used Young's modulus $E = 1.9 \times 10^{11} \text{ Pa}$ as given in Table 7.3 for the silicon beam in the above calculation.

We assumed that the strain in the beam will result in the same strain in the attached PZT film. Thus with a strain of $123.87 \times 10^{-5} \text{ m/m}$ in the PZT, the induced voltage per meter in the crystal is:

$$V = \frac{\epsilon}{d} = \frac{\epsilon_{\max}}{d} = \frac{123.87 \times 10^{-5}}{480 \times 10^{-12}} = 0.258 \times 10^7 \text{ V/m}$$

We used the piezoelectric coefficient $d = 480 \times 10^{-12} \text{ m/V}$ obtained from Table 7.14 in the above computation.

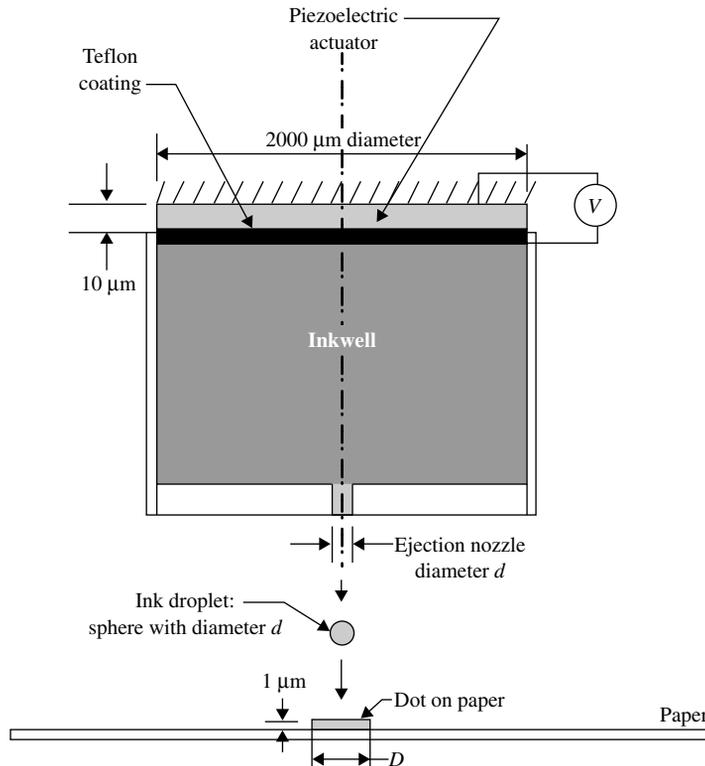
Since the actual length of the PZT crystal attached to the beam is $l = 4 \mu\text{m}$, we will expect the total voltage generated by the transducer at 10g load to be:

$$v = Vl = (0.258 \times 10^7)(4 \times 10^{-6}) = 10.32 \text{ V}$$

EXAMPLE 7.5

Determine the electric voltage required to eject a droplet of ink from an inkjet printer head with a PZT piezoelectric crystal as a pumping mechanism. The ejected ink will have a resolution of 300 dots per inch (dpi). The ink droplet is assumed to produce a dot with a film thickness of $1 \mu\text{m}$ on the paper. The geometry and dimension of the printer head is illustrated in Figure 7.19. Assume that the ink droplet takes the shape of a sphere and the inkwell is always refilled after ejection.

Figure 7.19 | Schematic diagram of an inkjet printer head.



Solution

We will first have to determine the diameter of the ejection nozzle, d , corresponding to ink dots with 300-dpi resolution on the paper. We will first determine the diameter of the dot, D , on the paper. With 300 such dots in a linear space of 1 in, we can readily find the corresponding diameter to be $D = 1 \text{ in}/300 = 25.4 \text{ mm}/300 = 0.084666 \text{ mm}$, or $84.67 \mu\text{m}$.

Since the dots are produced from spherical droplets of diameter d , by letting the volume of the ink droplet from the nozzle be equal to that of the ink dot on the paper, the following relation can be used:

$$\frac{4}{3} \pi r^3 = \left(\frac{\pi}{4} D^2\right)(t)$$

in which r = radius of the spherical ink droplet and t is the thickness of the ink dot on the paper. We thus find the radius of the spherical ink droplet, $r = 11.04 \times 10^{-6} \text{ m}$, with $D = 84.67 \mu\text{m}$ and $t = 1 \mu\text{m}$.

Next, we assume that the volume of an ink droplet leaving the inkwell is equivalent to the volume created by vertical expansion of the PZT piezoelectric cover at the back of the inkwell. Let the vertical expansion of the piezoelectric cover be W and the corresponding volume of the displaced ink be $(\pi/4) \Delta^2 W$, in which Δ is the diameter of the piezoelectric cover at $2000 \mu\text{m}$.

By equating the above displaced ink volume and the volume of the ink dot, V_{dot} , we can compute the required piezoelectric expansion W to be:

$$W = \frac{4V_{\text{dot}}}{\pi \Delta^2} = \frac{4 \times 5629.21 \times 10^{-18}}{3.1416(2000 \times 10^{-6})^2} = 1791.83 \times 10^{-12} \text{ m}$$

The corresponding strain in the piezoelectric cover is:

$$\varepsilon = \frac{W}{L} = \frac{1791.83 \times 10^{-12}}{10 \times 10^{-6}} = 179.183 \times 10^{-6} \text{ m/m}$$

From Equation (7.11) and the piezoelectric coefficient of PZT crystals from Table 7.14, we have the required applied voltage per meter as:

$$V = \frac{\varepsilon}{d} = \frac{179.183 \times 10^{-6}}{480 \times 10^{-12}} = 0.3733 \times 10^6 \text{ V/m}$$

Since the cover has a thickness of $10 \mu\text{m}$, the required applied voltage is:

$$v = LV = (10 \times 10^{-6})(0.3733 \times 10^6) = 3.733 \text{ V}$$

7.10 | POLYMERS

Polymers, which include such diverse materials as plastics, adhesives, Plexiglas, and Lucite, have become increasingly popular materials for MEMS and microsystems. For example, plastic cards approximately 150 mm wide containing over 1000 microchannels have been adopted in microfluidic electrophoretic systems by

the biomedical industry [Lipman 1999] as described in Chapter 2. Epoxy resins and adhesives such as silicone rubber are customarily used in MEMS and microsystem packaging.

This type of material is made up of long chains of organic (mainly hydrocarbon) molecules. The combined molecules, i.e., polymer molecules, can be a few hundred nanometers long. Low mechanical strength, low melting point, and poor electrical conductivity characterize polymers. Thermoplastics and thermosets are two groups of polymers that are commonly used for industrial products. Thermoplastics can be easily formed to the desired shape for the specific product, whereas thermosets have better mechanical strength and temperature resistance up to 350°C. Because of the rapid increase of applications in industrial products, polymers and polymerization, which is the process of producing various kinds of polymers, constitute a distinct engineering subject. It is not realistic to offer a complete list of available polymers and plastics, as well as the many polymerization processes in this chapter. What will be presented in this section is information on the applications of polymers that are relevant to the design and packaging of MEMS and microsystems. Much of the materials presented here are available in greater detail in a special reference on polymers for electronics and optoelectronics [Chilton and Goosey 1995].

7.10.1 Polymers as Industrial Materials

Traditionally, polymers have been used as insulators, sheathing, capacitor films in electric devices, and die pads in integrated circuits. A special form of polymer, the plastics, has been widely used for machine and device components. Following is a summary of the many advantages of polymers as industrial materials:

- Light weight
- Ease in processing
- Low cost of raw materials and processes for producing polymers
- High corrosion resistance
- High electrical resistance
- High flexibility in structures
- High dimensional stability

Perhaps the most intriguing fact about polymers is their variety of molecular structures. This unique feature has offered scientists and engineers great flexibility in developing “organic alloys” by mixing various ingredients to produce polymers that satisfy specific applications. Consequently, there are a great variety of polymers available for industrial applications in today’s marketplace.

7.10.2 Polymers for MEMS and Microsystems

Polymers have become increasingly important materials for MEMS and microsystems. Some of these applications are:

1. Photoresist polymers are used to produce masks for creating desired patterns on substrates by photolithography, as will be described in Chapter 8.

2. The same photoresist polymers are used to produce the prime mold with the desired geometry of MEMS components in the LIGA process for manufacturing microdevice components, as will be described in Chapter 9. These prime molds are plated with metals such as nickel for subsequent injection molding for mass production of microcomponents.
3. As will be described later in this subsection, conductive polymers are used as organic substrates for MEMS and microsystems.
4. The ferroelectric polymers, which behave like piezoelectric crystals, can be used as a source of actuation in microdevices such as those for micropumping, as described in Section 5.6.3 in Chapter 5.
5. The thin Langmuir–Blodgett (LB) films can be used to produce multilayer microstructures, similar to the micromachining technique presented in Chapter 9.
6. Polymers with unique characteristics are used as a coating substances for capillary tubes to facilitate electro-osmotic flow in microfluidics as described in Section 3.8.2.
7. Thin polymer films are used as electric insulators in microdevices and as a dielectric substances in microcapacitors.
8. Polymers are widely used for electromagnetic interference (EMI) and radio-frequency interference (RFI) shielding in microsystems.
9. Polymers are ideal materials for the encapsulation of microsensors and packaging of other microsystems.

7.10.3 Conductive Polymers

For polymers to be used in certain applications in microelectronics, MEMS, and microsystems, they have to be made electrically conductive with superior dimensional stability. Polymers have been used extensively in the packaging of MEMS, but they have also been used as substrates for some MEMS components in recent years with the successful development of techniques for controlling the electric conductivity of these materials.

By nature, polymers are poor electric conductors. Table 7.15 shows the electric conductivity of various materials. One will readily see that polymers, represented by polyethylene, have the lowest electric conductance of all the listed materials.

Polymers can be made electrically conductive by the following three methods:

Pyrolysis A pyropolymer based on phthalonitrile resin can be made electrically conductive by adding an amine heated above 600°C. The conductivity of the polymer produced by this process can be as high as 2.7×10^4 S/m, which is slightly better than that of carbon.

Doping Doping with the introduction of an inherently conductive polymer structure, such as by incorporating a transition metal atom into the polymer backbone, can result in electrically conductive polymers. Doping of polymers depends on the dopants and the individual polymer. Following are examples of dopants used in producing electrically conductive polymers:

Table 7.15 | Electric conductivity of selected materials

Materials	Electric conductivity, S/m*
<i>Conductors:</i>	
Copper	10^6 – 10^8
Carbon	10^4
<i>Semiconductors:</i>	
Germanium	10^0
Silicon	10^{-4} – 10^{-2}
<i>Insulators:</i>	
Glass	10^{-10} – 10^{-8}
Nylon	10^{-14} – 10^{-12}
SiO ₂	10^{-16} – 10^{-14}
Polyethylene	10^{-16} – 10^{-14}

*S/m = siemens per meter. Siemens = $\Omega^{-1} = \text{A}^2\text{-s}^3/\text{kg}\text{-m}^2$

For polyacetylenes (PA): Dopants such as Br₂, I₂, AsF₅, HClO₄, and H₂SO₄ are used to produce the p-type polymers, and sodium naphthalide in tetrahydrofuran (THF) is used for the n-type polymers.

For polyparaphenylenes (PPP): AsF₅ is used for the p-type and alkali metals are used for the n-type polymer.

For polyphenylene sulfide (PPS): The dopant used in this case is AsF₅.

Insertion of Conductive Fibers Incorporating conductive fillers into both thermosetting and thermoplastic polymer structures can result in electrically conductive polymers. Fillers include such materials as carbon, aluminum flakes, and stainless steel, gold, and silver fibers. Other inserts include semiconducting fibers, e.g., silicon and germanium. Fibers are in the order of nanometers in length.

7.10.4 The Langmuir–Blodgett (LB) Film

A special process developed by Langmuir as early as 1917, and refined by Blodgett, can be used to produce thin polymer films at molecular scale. This process is generally known as the *LB process*. It involves spreading volatile solvent over surface-active materials. The LB process can produce more than a single monolayer by depositing films of various compositions onto a substrate to create a multilayer structure. The process closely resembles that of the micromachining manufacturing technique presented in Chapter 9. It is thus regarded as an alternative micromanufacturing technique.

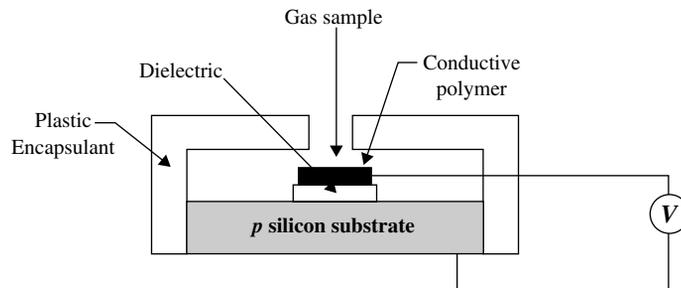
LB films are good candidate materials for exhibiting ferro (magnetic), pyro (heat-generating), and piezoelectric properties. LB films may also be produced with controlled optical properties such as refractive index and antireflectivity. They are thus ideal materials for microsensors and optoelectronic devices. Following are a few examples of LB film applications in microsystems:

1. *Ferroelectric polymer thin films.* Useful in particular is polyvinylidene fluoride (PVDF). Applications of this type of film include sound transducers in air and water, tactile sensors, biomedical applications such

as tissue-compatible implants, cardiopulmonary sensors, and implantable transducers and sensors for prosthetics and rehabilitation devices. The piezoelectric coefficient of PVDF is given in Table 7.14.

2. *Coating materials with controllable optical properties.* These are widely used in broadband optical fibers, which can transmit laser light at different wavelengths.
3. *Microsensors.* The sensitivity of many electrically conducting polymeric materials to the gases and other environmental conditions makes this material suitable for microsensors. Its ability to detect specific substances relies on the reversible and specific absorption of species of interest on the surface of the polymer layer and the subsequent measurable change of conductivity of the polymer. Figure 7.20 shows a schematic structure of such a sensor. These sensors work on the principle that the electric conductivity of the polymer sensing element will change when it is exposed to a specific gas. This principle is similar to that of chemical sensors as described in Chapter 2.

Figure 7.20 | Microsensor using polymers.



Conductive polymers are also used in electrochemical biosensors, such as microamperometric glucose and galactose biosensors.

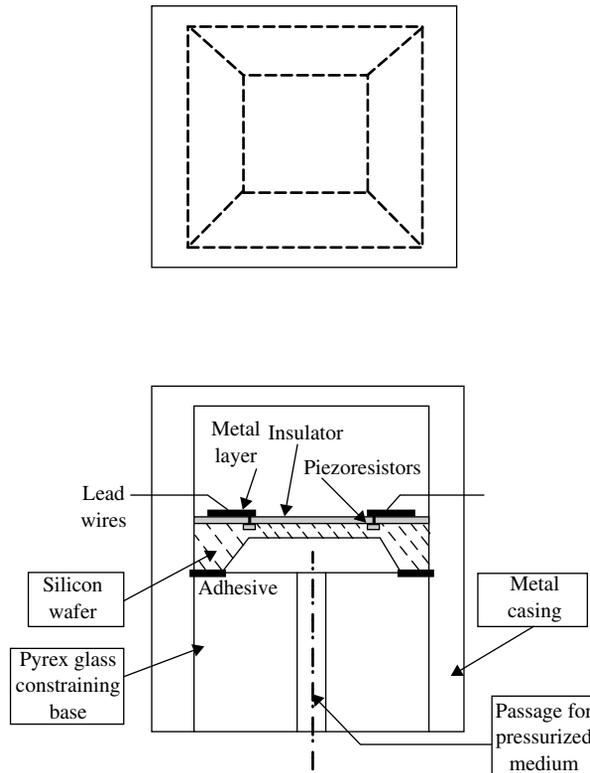
7.11 | PACKAGING MATERIALS

We learned about the evolution of micromachining technology from the integrated circuits industry in Chapter 1. Consequently, many techniques that were developed for the IC packaging are now used for microsystems packaging. However, a major distinction between the two types of packaging is that in microelectronics packaging, it is usually sufficient to protect the IC die and the interconnects from the often hostile operating environment. In microsystem packaging, however, not only are the sensing or actuating elements to be protected, but they are also required to be in contact with the media that are the sources of actions. Many of these media are hostile to these elements. Special technologies that have been developed to package delicate aerospace device components are also used frequently in the packaging of microsystems.

Materials used in microsystem packaging include those used in IC packaging—wires made of noble metals at the silicon die level, metal layers for lead wires,

solders for die/constraint base attachments, etc. Microsystems packaging also include metals and plastics. Let us take a look at a typical pressure sensor, schematically shown in Figure 7.21. At the die level, we use aluminum or gold metal films as the ohmic contacts to the piezoresistors that are diffused in the silicon diaphragm. Similar materials are used for the lead wires to the interconnects outside the casing. The casing can be made of plastic or stainless steel, depending on the severity of the environment. Glass such as Pyrex or ceramics such as alumina are often used as constraint bases. The adhesives that enable the silicon die to be attached to the constraint base can be tin-lead solder alloys or epoxy resins or adhesives such as the popular Room-temperature vulcanizing (RTV) silicone rubber. In the case of soldered attachments, thin metal layers need to be sputtered at the joints to facilitate the soldering. Copper and aluminum are good candidate materials for this purpose. We will learn from Chapter 11 that these adhesive materials for die/base attachments are very important in isolating the die from undesired interference from other components in the package. When part of a microsystem package, such as silicon diaphragm, needs to be in contact with a hostile medium, silicone gel or silicone oil is used to shield the part.

Figure 7.21 | A typical packaged micropressure sensor.



PROBLEMS

Part I. Multiple Choice

1. A substrate is (1) a sublayer in MEMS, (2) a flat microscopic object, (3) a flat macroscopic object in microelectronics.
2. A semiconducting material can be made to become an electrically conducting material by (1) applying high electric voltage, (2) applying high current, (3) introducing the right kind of foreign atoms into the semiconducting material.
3. Silicon has a Young's modulus similar to that of (1) aluminum, (2) stainless steel, (3) copper.
4. Silicon has a mass density similar to that of (1) aluminum, (2) stainless steel, (3) copper.
5. The principal reason why silicon is an ideal material for MEMS is (1) its dimensional stability over a wide range of temperatures, (2) it is light and strong, (3) it is readily available.
6. Silicon has a coefficient of thermal expansion (1) higher than, (2) lower than, (3) about the same as that of silicon dioxide.
7. The 300-mm wafers offer (1) 2, (2) 2.25, (3) 2.5 times more area for substrates than that by 200-mm wafers.
8. The length of the lattice of a silicon crystal is (1) 0.543, (2) 0.643, (3) 0.743 nanometer.
9. Miller's indices are used to designate (1) the length, (2) the plane, (3) the volume of a face-centered cubic crystal.
10. The (100) plane in a silicon crystal consists of (1) 5, (2) 8, (3) 6 atoms.
11. The (110) plane in a silicon crystal consists of (1) 5, (2) 8, (3) 6 atoms.
12. The (111) plane in a silicon crystal consists of (1) 5, (2) 8, (3) 6 atoms.
13. The growth of silicon crystals is slowest in the (1) $\langle 100 \rangle$, (2) $\langle 110 \rangle$, (3) $\langle 111 \rangle$ direction.
14. Silicon conducts heat (1) 50, (2) 150, (3) 200 times faster than silicon oxide.
15. Silicon carbide films are used to protect (1) the underlying substrates, (2) the integrated circuits, (3) the electric interconnects in a microsystem.
16. Silicon nitride is (1) tougher than, (2) weaker than, (3) about the same as silicon in strength.
17. Pure and single-crystal silicon (1) exists in nature, (2) is grown from special processes, (3) is made by electrolysis.
18. Wafers used in MEMS and microelectronics are (1) the products of a single-crystal silicon boule, (2) are synthesized from silicon compounds, (3) exist in nature.
19. MEMS design engineers are advised to adopt (1) any size, (2) a custom-specified size, (3) an industrial standard size of wafer.
20. The total number of atoms in a silicon unit crystal is (1) 18, (2) 16, (3) 14.

21. The toughest plane for processing in a single silicon crystal is (1) the (100) plane, (2) the (110) plane, (3) the (111) plane.
22. The 54.74° slope in the cavity of a silicon die for a pressure sensor is (1) determined by choice, (2) a result of the crystal's resistance to etching in the (111) plane, (3) a result of the crystal's resistance to etching in the (110) plane.
23. Polysilicon is popular because it can easily be made as a (1) semiconductor, (2) insulator, (3) electrical conductor.
24. Polysilicon films are used in microsystems as (1) dielectric material, (2) substrate material, (3) electrically conducting material.
25. The electrical resistance of silicon piezoresistors varies in (1) all directions, (2) only in the preferred directions, (3) neither of the above applies.
26. It is customary to relate silicon piezoresistance change to (1) deformations, (2) strains, (3) stresses induced in the piezoresistors in MEMS and microsystems.
27. There are (1) three, (2) four, (3) six piezoresistive coefficients in silicon piezoresistors.
28. The single most serious disadvantage of using silicon piezoresistor is (1) the high cost of producing such resistors, (2) its strong sensitivity to signal transduction, (3) its strong sensitivity to temperature.
29. Gallium arsenide has (1) 6, (2) 7, (3) 8 times higher electron mobility than silicon.
30. Gallium arsenide is chosen over silicon for the use in micro-optical devices because of its (1) optical reflectivity, (2) dimensional stability, (3) high electron mobility.
31. Gallium arsenide is not as popular as silicon in MEMS application because of (1) its higher cost in production, (2) difficulty of mechanical work, (3) low mechanical strength.
32. Quartz crystals have the shape of (1) a cube, (2) a tetrahedron, (3) a body-centered cube.
33. It is customary to relate the voltage produced by a piezoelectric crystal to the (1) deformations, (2) temperature, (3) stresses induced in the crystal.
34. Application of mechanical deformation to a piezoelectric crystal can result in the production of (1) electric resistance change, (2) electric current change, (3) electric voltage change in the crystal.
35. Most piezoelectric crystals (1) exist in nature, (2) are made by synthetic processes, (3) are made by doping the substrate.
36. A polymer is a material that is made up of many (1) small-size, (2) large-size, (3) long-chain molecules.
37. In general, polymers are (1) electrically conductive, (2) semi electrically conductive, (3) insulators.
38. Polymers (1) can, (2) cannot, (3) may never be made electrically conductive.

39. The LB process is used to produce (1) thin films, (2) dies, (3) piezoelectric polymers in MEMS and microsystems.
40. MEMS and microsystem packaging materials are (1) restricted to microelectronics packaging materials, (2) just about all engineering materials, (3) semiconducting materials.

Part 2. Computational Problems

1. Estimate the maximum number of silicon dies of size of 2 mm wide \times 4 mm long that can be accommodated in the four standard-sized wafers given in Section 7.4.2. The dies are laid out in parallel on the wafer with 0.25- μm gaps between dies. Make your observation on the results.
2. Prove that the 300-mm wafers do indeed have 2.25 times larger area for substrates than that of 200-mm wafers.
3. Estimate the number of atoms per cubic millimeter and cubic micrometer of pure silicon.
4. Find the change of electric resistance if a piezoresistor made of p-type silicon replaces the piezoelectric crystal in Example 7.4. The piezoresistor has a length of 4 μm .
5. What would be the voltage output of the piezoelectric transducer in Example 7.4 if PVDF polymer films were used instead?
6. Determine the length of lattices that bond the atoms in the three principal planes of the silicon crystal shown in Figure 7.8.
7. Determine the spacing between atoms in the three planes in a single silicon crystal as illustrated in Figure 7.10.
8. Determine the angle between the orientation $\langle 100 \rangle$ to the (111) plane in a single silicon crystal cell.
9. For homogeneous and isotropic solids, the relation between the three elastic constants is $E = 2(1 + \nu)G$ exists. In this relationship, E is the Young's modulus, ν is Poisson's ratio, and G is the shear modulus of elasticity. Determine the Young's modulus of silicon in three orientations in Table 7.2 using the tabulated values of ν and G , and compare the computed results with those tabulated.
10. Determine the electric voltage required to pump a droplet of ink from the well in Example 7.5 with a resolution of 600 dpi.