Chapter 7 Materials for MEMS and Microsystems

7.1 Introduction

- Many Microsystems use microelectronics materials such as silicon, and gallium arsenide (GaAs, 砷化鎵) for the sensing and actuating elements.
  - Reasons: (1) dimensionally stable;
    (2) well-established fabricating and packaging techniques.

- However, there are other materials used for MEMS and Microsystems products:
  - Such as quartz and Pyrex (派萊克斯耐熱玻璃), polymers and plastics, and ceramics. (not common in microelectronics)

7.2 Substrates and Wafers

- Substrate (基底):
  - ➢ In microelectronics, substrate is a flat macroscopic object on which microfabrication processes take place [Ruska, 1987].
  - ➢ In microsystems, a substrate serves an additional purpose:
    - Act as signal transducer besides supporting other transducers that convert mechanical actions to electrical outputs or vice versa.

- Wafer (晶片, 晶圓):
  - ➢ In semiconductors, the substrate is a single crystal cut in slices from a larger piece call a wafer (which can be of silicon or other single crystalline materials such as quartz or gallium arsenide).
  - ➢ In microsystems, there are two types of substrate materials:
    1. Active substrate material.
    2. Passive substrate material.

- Material classifications:
  - ➢ Insulators: electric resistivity $\rho > 10^8\ \Omega$-cm
  - ➢ Semiconductors: $10^{-3} < \rho < 10^8\ \Omega$-cm
  - ➢ Conductors: $\rho < 10^{-3}\ \Omega$-cm

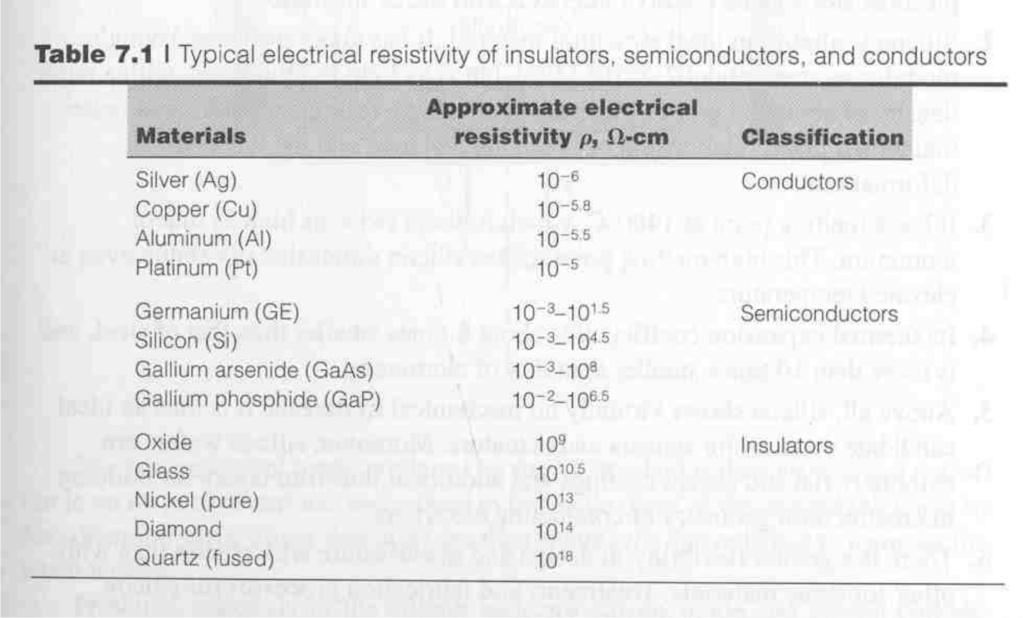


Table 7.1 | Typical electrical resistivity of insulators, semiconductors, and conductors

Materials	Approximate electrical resistivity ρ, Ω-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}–$10^{1.5}$	Semiconductors
Silicon (Si)	10^{-3}–$10^{4.5}$	
Gallium arsenide (GaAs)	10^{-3}–10^{8}	
Gallium phosphide (GaP)	10^{-2}–$10^{6.5}$	
Oxide	10^{9}	Insulators
Glass	$10^{10.5}$	
Nickel (pure)	10^{13}	
Diamond	10^{14}	
Quartz (fused)	10^{18}	

- In MEMS, common substrate materials (silicon Si, germanium Ge 鍺, gallium arsenide GaAs) all fall in the category of semiconductors. Why?
  - They are at the borderline between conductors and insulators, so they can be made either a conductor or an insulator as needed.
    → Can be converted to a conducting material by doping (p- or n-type).
  - The fabrication processes (e.g., etching) and the required equipment have already been developed for these materials.

7.3 Active Substrate Materials

- Active substrate materials are primarily used for sensors and actuators in Microsystems (Fig. 1.5).
  - Typical materials: Si, GaAs, Ge, and quartz.
    (All except quartz are classified as semiconductors in Table 7.1)
  - Have a cubic crystal lattice with tetrahedral (四面體的) atomic bond.
  - Reason for active substrate materials: dimensional stability
    → Insensitive to environmental conditions.
    → A critical requirement for sensors and actuators with high precision.
  - Each atom carries 4 electrons in the outer orbit, and shares these 4 electrons with its 4 neighbors.

7.4 Silicon as A substrate Material

7.4.1 The Ideal Substrate for MEMS

- Single-crystal silicon is the most widely used substrate material for MEMS and microsystem. The reasons are:
  1. (a) Mechanically stable; (b) can be integrated with electronics for signal transduction on the same substrate.
  2. An ideal structural material because of high Young’s modulus (which can better maintain a linear relationship between applied load and the induced deformation) and light weight.
     - About the same as steel (about 2×10^5 MPa)
     - As light as aluminum with a mass density of about 2.3 g/cm^3.
  3. High melting point at 1400℃
     - About twice as high as that of aluminum.
     - Dimensionally stable.
  4. Low thermal expansion coefficient
     - About 8 times smaller than that of steel.
     - More than 10 times smaller than that of aluminum.
  5. (a) Show virtually no mechanical hysteresis (遲滯).

     → An ideal candidate material for sensors and actuators.

     (b) Extremely flat and accept coatings and additional thin-film layers for building microstructures and conducting electricity.
  6. Treatment and fabrication processes for silicon substrate are well established and documented.

7.4.2 Single Crystal Silicon and Wafer

- The Czochralski (CZ) method: is the most popular one to produce pure silicon crystal. (Fig. 7.1)
  - The raw silicon in the form of quartzite (石英岩) are melted in a quartz crucible (坩堝, 熔爐之底部) with carbon (coal, coke, wood chips, etc.), which is placed in a furnace.

    $$SiC+SiO_2 \rightarrow Si+CO+SiO$$
  - A “seed” crystal is brought into contact with the molten silicon to form a larger crystal (a large bologna-shaped boule [人造寶石]).
  - The silicon boule is then ground to a perfect circle, then sliced to form thin disks, which are then chemically-lap (磨平) polished for finishing.

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

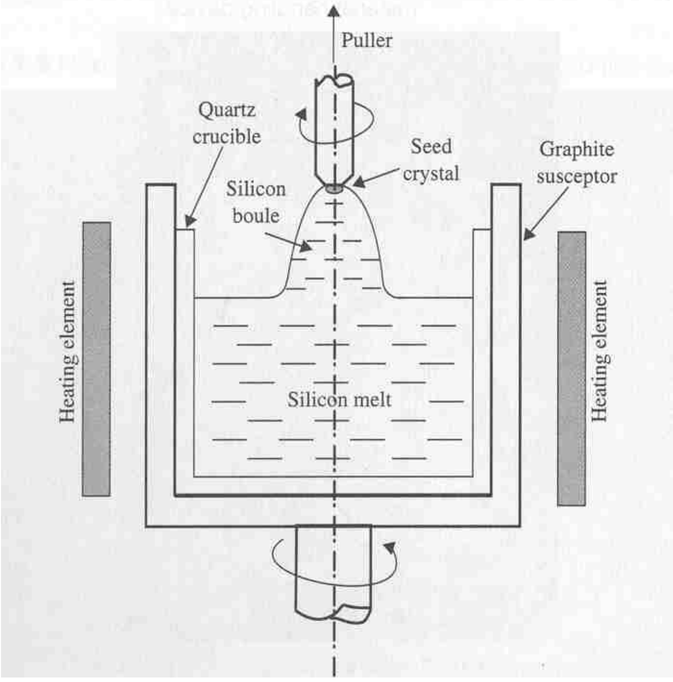
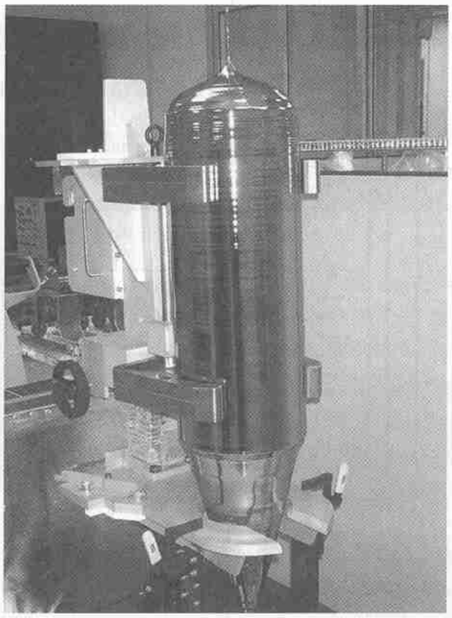


Figure 7.2 I A 300-mm single-crystal silicon boule cooling on a material-handling device.



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

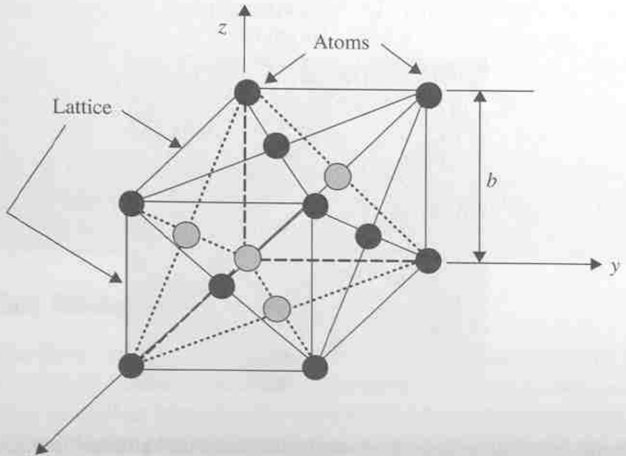
- Wafer sizes:
  - 100 mm (4 in) diameter × 500 μm thick
  - 150 mm (6 in) diameter × 750 μm thick
  - 200 mm (8 in) diameter × 1mm thick
  - 300 mm (12 in) diameter × 750 μm thick (tentative)

- Silicon substrates often are expected to carry electric charges.
  - Require p or n doping of the wafers either by ion implantation or by diffusion (see Sec. 3.5 and Chapter 8).
  - n-type dopants: phosphorus [P, 磷], arsenic [As, 砷], and antimony[Sb, 銻]
  - p-type dopants: boron [B, 硼]

7.4.3 Crystal Structural

- Silicon: has basically a face-centered cubic (FCC) unit cell, called a *lattice* (as shown in Fig. 7.4).
  - Lattice constant b=0.543 nm.
  - Crystal structure of silicon: more complex
    - → two penetrating face-centered cubic crystals, as shown in Fig. 4.4.
    - → 4 additional atoms in the interior of the FCC.
    - → 18 atoms in a unit cell.
    - → spacing between adjacent atoms in the diamond subcell: 0.235 nm.
  - Asymmetrical and nonuniform lattice distance: exhibits anisotropic (非等相性的) thermophysical and mechanical characteristics.

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



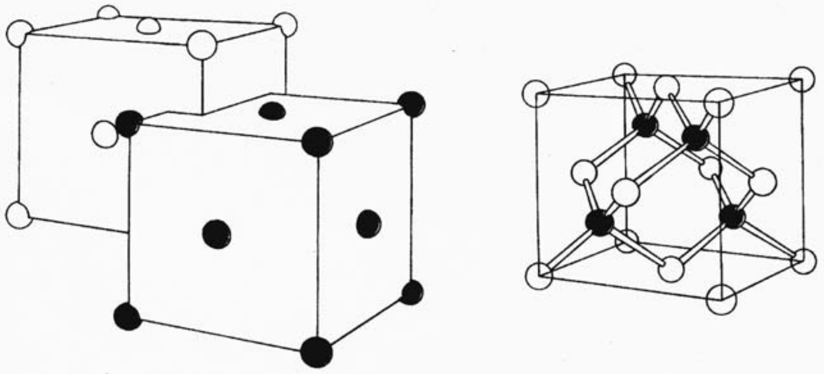


Figure 4.4 The diamond-type lattice can be constructed from two interpenetrating face-centered cubic unit cells. Si forms four covalent bonds, making tetrahedrons.

- Crystal structure of GaAs:

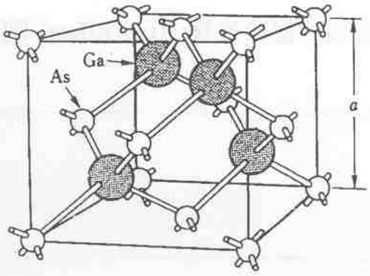


圖 4.1 砷化鎵的結晶結構

7.4.4 The Miller Indices

- Because of the skew (歪曲的) distribution of atoms in a silicon crystal, it is important to designate (指定) the principal orientations as well as planes in the crystal.

- Miller Indices:
  - A plane that intercepts x, y, and z axes at a, b, and c, can be expressed as:

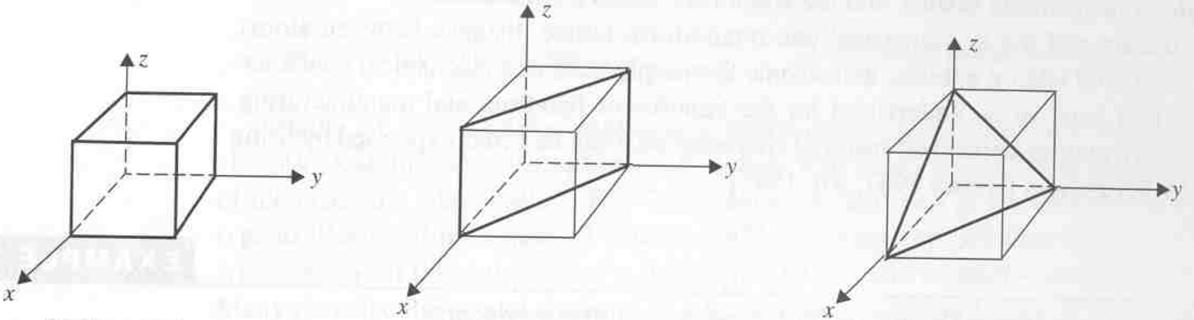
$$\frac{x}{a}+\frac{y}{b}+\frac{z}{c}=1 \tag{7.1}$$

  - Equation (7.1) can be rewritten as:

$$hx+ky+mz=1$$

    where h=1/a, k=1/b, and m=1/c.
  - (hkm): designate the plane, and <hkm>: designate the direction normal to the plane.
  - Examples:

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



(a) Normal planes (b) Diagonal plane (c) Inclined plane

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)

Figure 7.9 | Silicon crystal structure and planes and orientations.

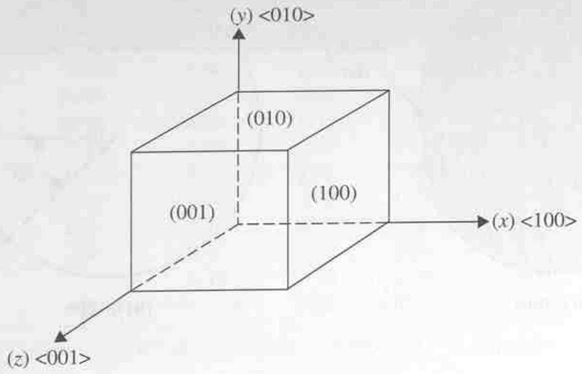
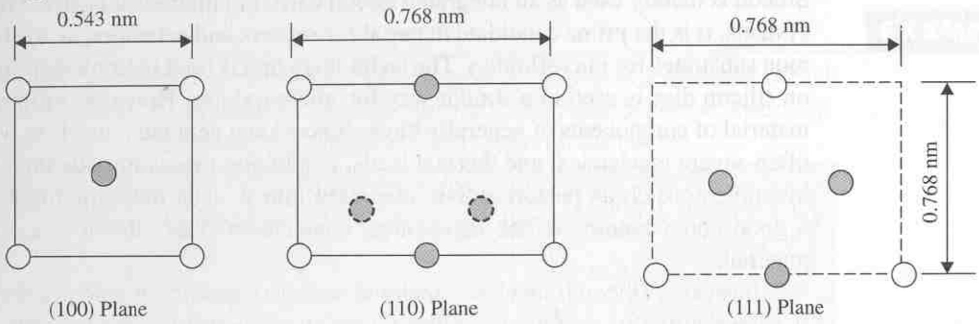


Figure 7.10 | Silicon atoms on three designated planes.



- In Fig. 7.10,
  - The lattice distances between adjacent atoms are shortest on (111) plane.
  - These shortest lattice distance makes the attractive forces between atoms stronger on (111) than those on the (100) and (110) planes.
  - On the (111) plane, the growth of crystal is the slowest, and the fabrication processes will proceed slowest.

- Primary flats and secondary flats are used to indicate the crystal orientation and dopant type of the wafers.

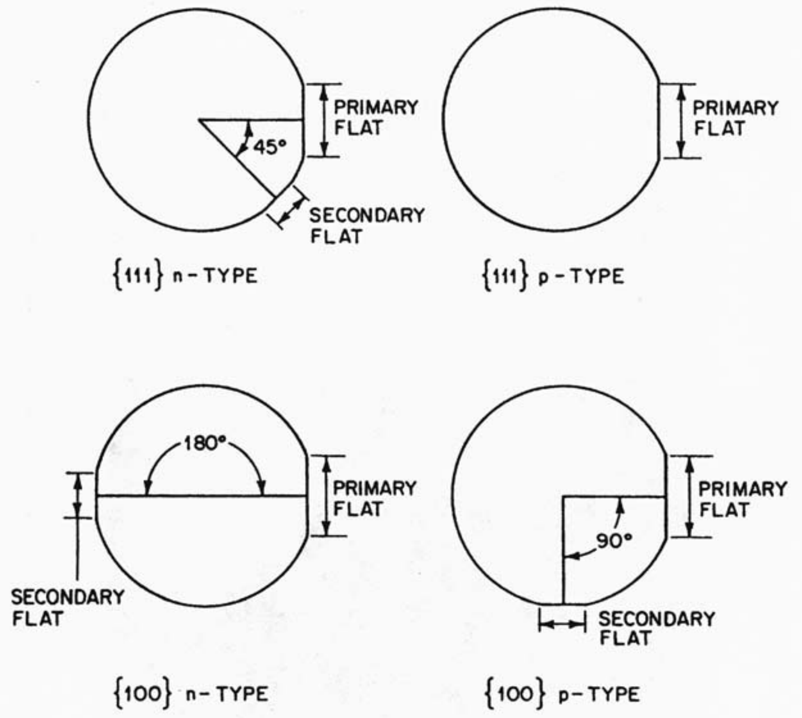


Figure 4.5 Primary and secondary flats on silicon wafers.

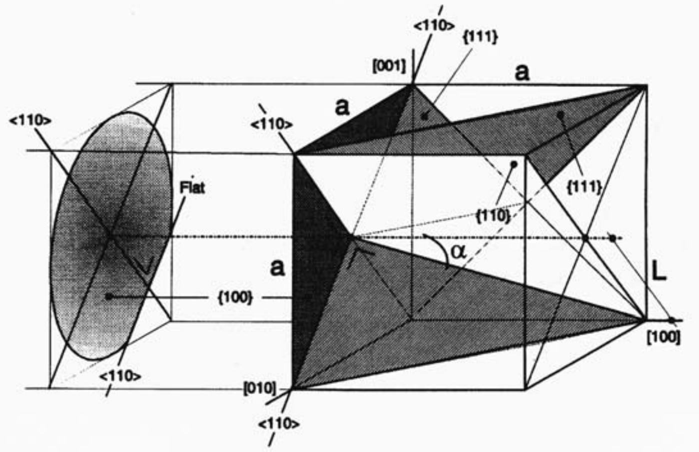


Figure 4.6 (100) silicon wafer with reference to the unity cube and its relevant planes. (From E. Peeters, "Process Development for 3D Silicon Microstructures, with Application to Mechanical Sensor Design," KUL, Belgium, 1994.[42] Reprinted with permission.)

(Madou, 1997)

7.4.5 Mechanical Properties of Silicon

- Silicon, as the material of 3-D structures, needs to withstand often-severe mechanical and thermal loads, in addition to accommodating electrical instruments.

- Silicon is an ideal sensing and actuating material because
  1. It is an elastic material with no plasticity (塑性) or creep (潛變, 金屬等逐漸變形) below 800℃.
  2. Show virtually no fatigue (疲乏) failure.

- Disadvantages:
  1. brittle (易碎的,脆的)
  2. weak resistance to impact loads
  3. anisotropic (非等向性的), which makes stress analysis of the structures tedious.

- Young's moduli and shear moduli in three directions:

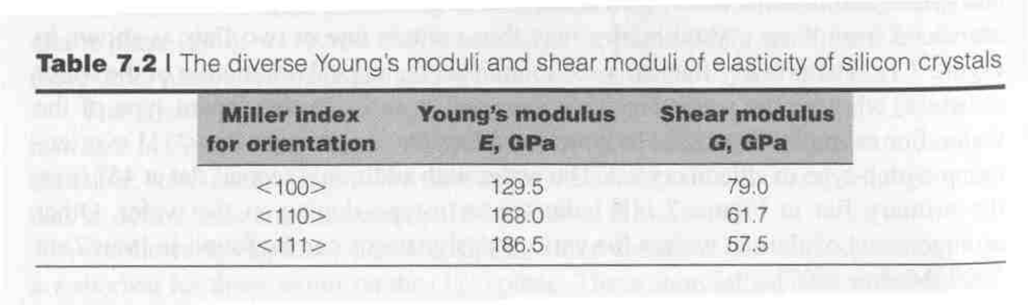


Table 7.2 I The diverse Young's moduli and shear moduli of elasticity of silicon crystals

Miller index for orientation	Young's modulus E, GPa	Shear modulus G, GPa
<100>	129.5	79.0
<110>	168.0	61.7
<111>	186.5	57.5

- Bulk material properties of silicon, silicon compounds, and other active substrate materials:

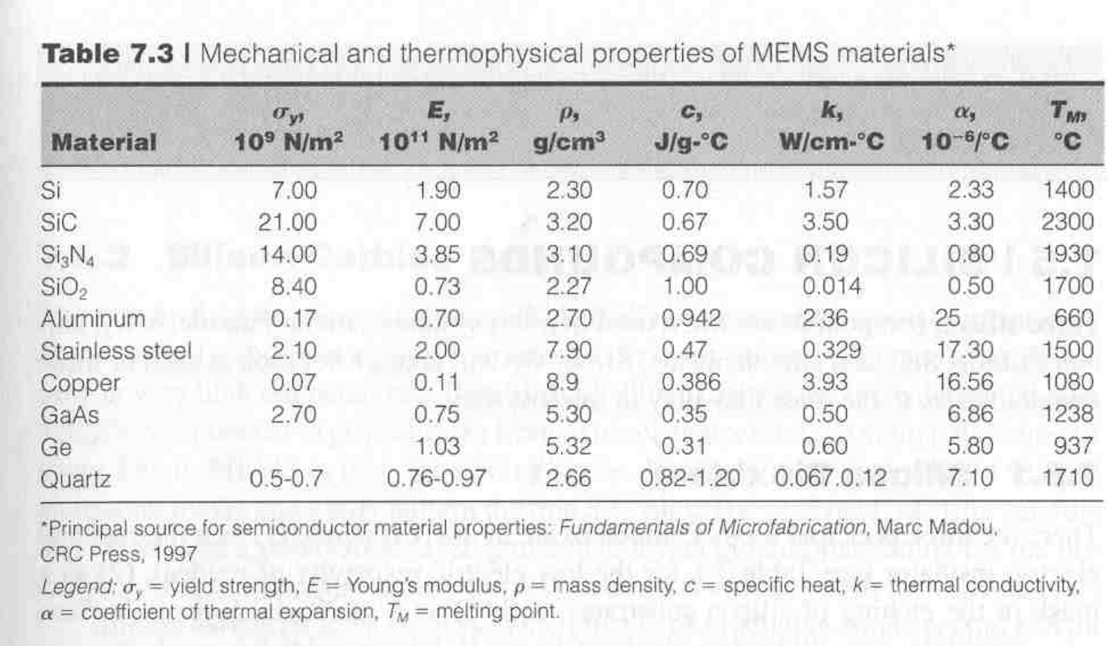


Table 7.3 I Mechanical and thermophysical properties of MEMS materials*

Material	σ_y, 10^9 N/m²	E, 10^{11} N/m²	ρ, g/cm³	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_3N_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.

7.5 Silicon Compounds

- 3 often-used silicon compounds:
  1. Silicon dioxide (SiO_2)
  2. Silicon Carbide (SiC)
  3. Silicon Nitride (Si_3N_4)

7.5.1 Silicon Dioxide (SiO_2)

- Three principal uses of SiO_2:
  1. as a thermal and electric insulator (see Table 7.1);
  2. as a mask (遮蓋物) in the etching of silicon substrates;
     (∵SiO_2 has much stronger resistance to most etchants than silicon)
  3. as a sacrificial layer (犧牲層) in the surface micromachining.

- Properties:

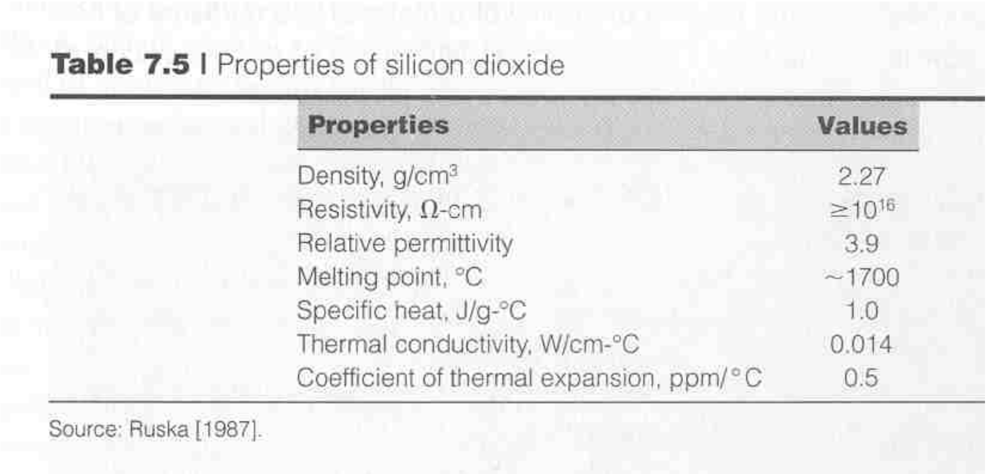


Table 7.5 | Properties of silicon dioxide

Properties	Values
Density, g/cm^3	2.27
Resistivity, Ω-cm	$\geq 10^{16}$
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].

- Oxidation: by heating silicon in an oxidant (e.g., O_2) with or without steam.
  (a) Dry oxidation:

$$Si + O_2 \rightarrow SiO_2$$

  (b) Wet oxidation in steam:

$$Si + 2H_2O \rightarrow SiO_2 + 2H_2$$

- Oxidation is effectively a diffusion process (see Chapter 3). Diffusivity of SiO_2 at 900℃ in dry oxidation:
  (a) $4\text{x}10^{-19}$ cm^2/s for arsenic(砷, As)-doped silicon (n-type);
  (b) $3\text{x}10^{-19}$ cm^2/s for boron(硼, B)-doped silicon (p-type);

Note: Steam would accelerate the oxidation process.

7.5.2 Silicon Carbide (SC)

- Properties and usages:
  1. dimensional and chemical stability at high temperature
     (a) strong resistance to oxidation at very high temperature
     (b) deposited over MEMS components to protect them from extreme temperature
  2. The thin SiC film can be patterned by dry etching with aluminum masks, and can be further used as passivation layer (protective layer) in micromachining for the underlying silicon layer.
     (∵ SiC can resist common etchants such as KOH and HF.)

- SiC: a by-product (副產品) in producing single crystal silicon boule (人造寶石).
  - ➢ Intense heating of the carbon raw materials (coal 煤, coke 焦煤, wood chips, etc.) would results in SiC sinking to the bottom of the crucible (坩堝).

- The SiC film: produced by various deposition techniques.
  - ➢ Table 7.3 lists some thermophysical properties.

7.5.3 Silicon Nitride (Si_3N_4)

- Superior properties attractive for MEMS:
  - ➢ An excellent barrier to diffusion of water and ions (e.g., sodium 鈉)
  - ➢ Ultrastrong resistance to oxidation and many etchants
    → Suitable for masks for deep etching.

- Applications:
  - Optical waveguides
  - Encapsulants (膠囊密封藥劑) to prevent diffusion of water and other toxic fluid into the substrate.
  - High-strength electric insulators and ion implantation masks.

- Production Processes:
  - ➢ Produced from silicon containing gases and NH_3:

$$3SiCl_2H_2 + 4NH_3 \rightarrow Si_3N_4 + 6HCl + 6H_2 \quad (7.5)$$

  - ➢ Can be produced by both LPCVD (low pressure chemical vapor deposition) and PECVD (plasma-enhanced chemical vapor deposition) processes. (chap8)
    Note: plasma - 電漿 (原子核與電子分離的氣體狀態)
  - ➢ Properties: listed in Tables 7.3 and 7.6.

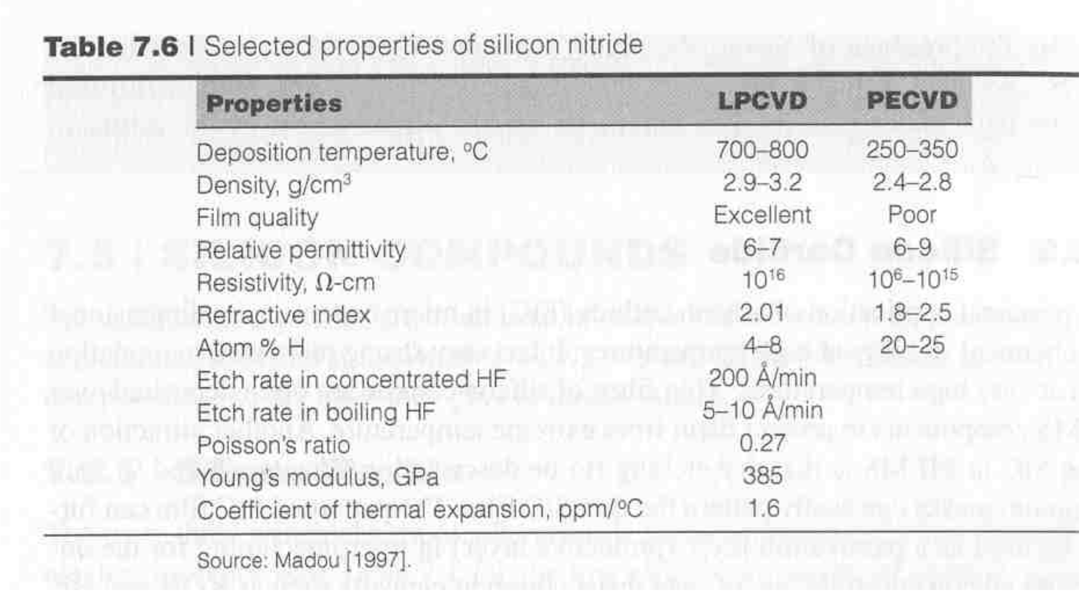


Table 7.6 | Selected properties of silicon nitride

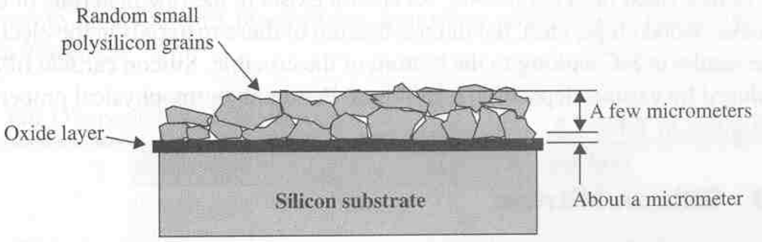
Properties	LPCVD	PECVD
Deposition temperature, °C	700–800	250–350
Density, g/cm^3	2.9–3.2	2.4–2.8
Film quality	Excellent	Poor
Relative permittivity	6–7	6–9
Resistivity, Ω-cm	10^{16}	10^{6}–10^{15}
Refractive index	2.01	1.8–2.5
Atom % H	4–8	20–25
Etch rate in concentrated HF	200 Å/min	
Etch rate in boiling 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].

7.5.4 Polycrystalline Silicon

- Polysilicon is a principal material in surface micromachining (see Chap.9).

Figure 7.12 | Polysilicon deposits on a silicon substrate.



- Production process:
  - LPCVD is frequently used for depositing polycrystalline silicon onto silicon.
    → Temperature: 600 to 650℃

- Applications and properties:
  - In IC industry: resistors, gates for transistors, thin-film transistors, etc.
  - Highly doped polysilicon can reduce the resistivity of polysilicon to produce conductors and control switches.
    → Ideal material for microresistors as well as easy ohmic contacts.
  - Polysilicon can be treated as isotropic material in structural and thermal analyses (due to its crystals in random sizes and orientations).
  - Table 7.7: list some key properties of polysilicon and other materials.

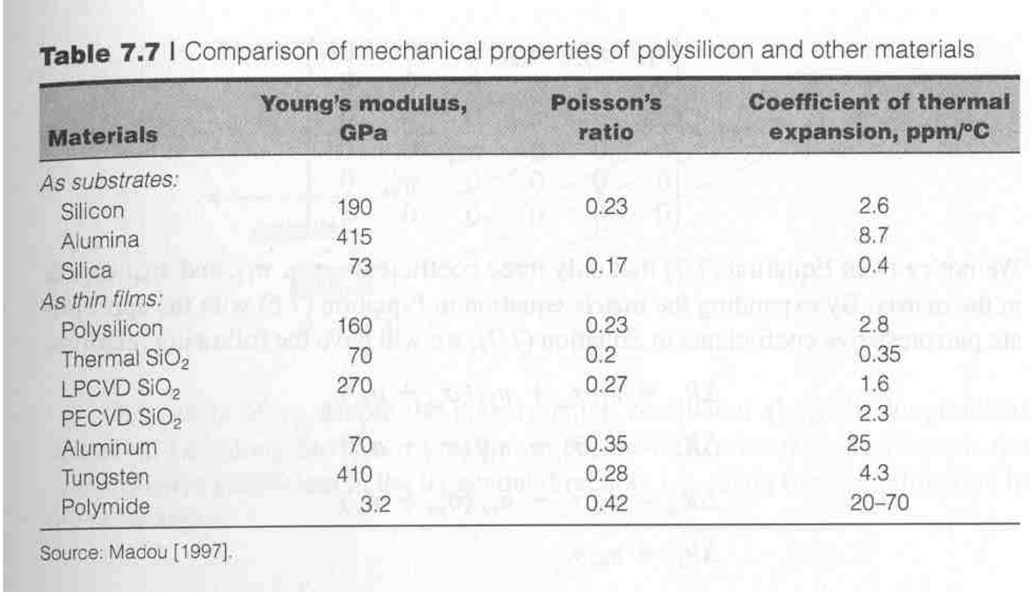


Table 7.7 | Comparison of mechanical properties of polysilicon and other materials

Materials	Young's modulus, GPa	Poisson's ratio	Coefficient of thermal expansion, ppm/°C
As substrates:			
Silicon	190	0.23	2.6
Alumina	415		8.7
Silica	73	0.17	0.4
As thin films:			
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].

7.6 Silicon Piezoresistors

- Definition of piezoresistance (壓阻):
  - A change in electric resistance of solids when subjected to stress fields.

- Both p- ad n-type silicon exhibit excellent piezoresistive effect.

- Due to anisotropic in p- and n-type silicon, the relationship between the resistance change and the stress field is more complex:

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

where $\{\Delta R\} = \{\Delta R_{xx} \quad \Delta R_{yy} \quad \Delta R_{zz} \quad \Delta R_{xy} \quad \Delta R_{xz} \quad \Delta R_{yz}\}^T$: change of resistance in an infinitesimally small cubic piezoresistive crystal element with corresponding stress components $\{\sigma\} = \{\sigma_{xx} \quad \sigma_{yy} \quad \sigma_{zz} \quad \sigma_{xy} \quad \sigma_{xz} \quad \sigma_{yz}\}^T$, and $[\pi]$: piezoresistive coefficient matrix, which has the form:

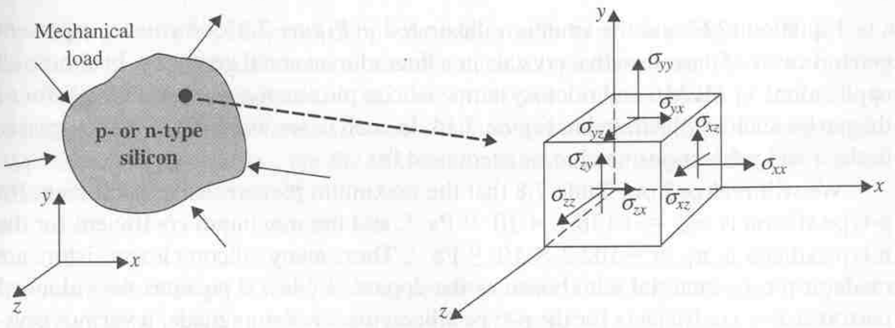
$$[\pi] = \begin{bmatrix} \pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \pi_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \pi_{44} \end{bmatrix} \tag{7.7}$$

- That is,

$$\Delta R_{xx} = \pi_{11}\sigma_{xx} + \pi_{12}\left(\sigma_{yy} + \sigma_{zz}\right)$$
$$\Delta R_{yy} = \pi_{11}\sigma_{yy} + \pi_{12}\left(\sigma_{xx} + \sigma_{zz}\right)$$
$$\Delta R_{zz} = \pi_{11}\sigma_{zz} + \pi_{12}\left(\sigma_{xx} + \sigma_{yy}\right)$$
$$\Delta R_{xy} = \pi_{44}\sigma_{xy}$$
$$\Delta R_{xz} = \pi_{44}\sigma_{xz}$$
$$\Delta R_{yz} = \pi_{44}\sigma_{yz}$$

- π_{11} and π_{12} are associated with the normal stress components, whereas π_{44} is related to the shearing stress components.

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



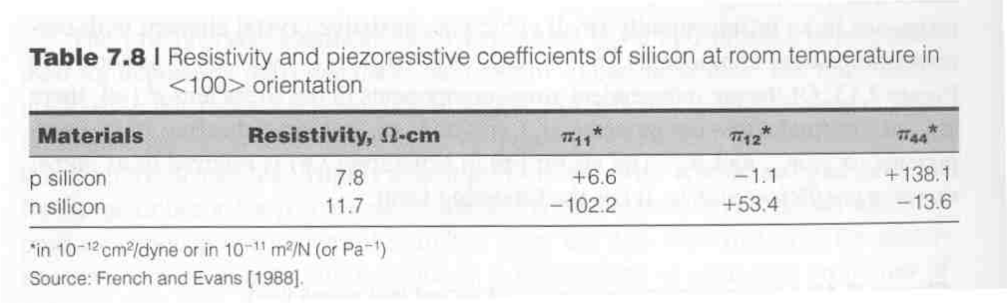


Table 7.8 | Resistivity and piezoresistive coefficients of silicon at room temperature in <100> orientation

Materials	Resistivity, Ω-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

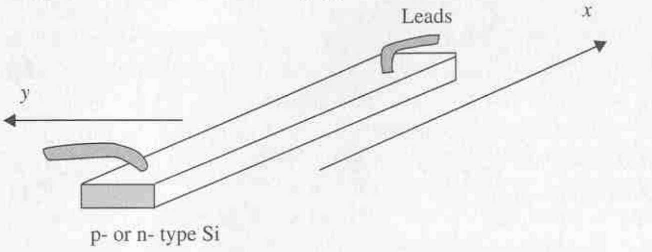
*in 10^{-12} cm²/dyne or in 10^{-11} m²/N (or Pa⁻¹)
Source: French and Evans [1988].

- In Fig 7.14, The change of electric resistance can be expressed as

$$\frac{\Delta R}{R} = \pi_L\sigma_L + \pi_T\sigma_T \qquad (7.8)$$

where π_L and π_T denote the piezoresistive coefficients along the longitudinal and tangential directions, respectively.

Figure 7.14 | Silicon strain gages.



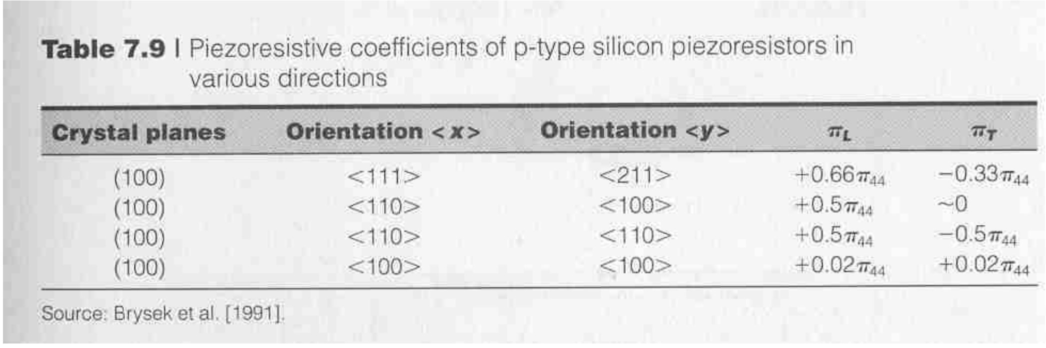
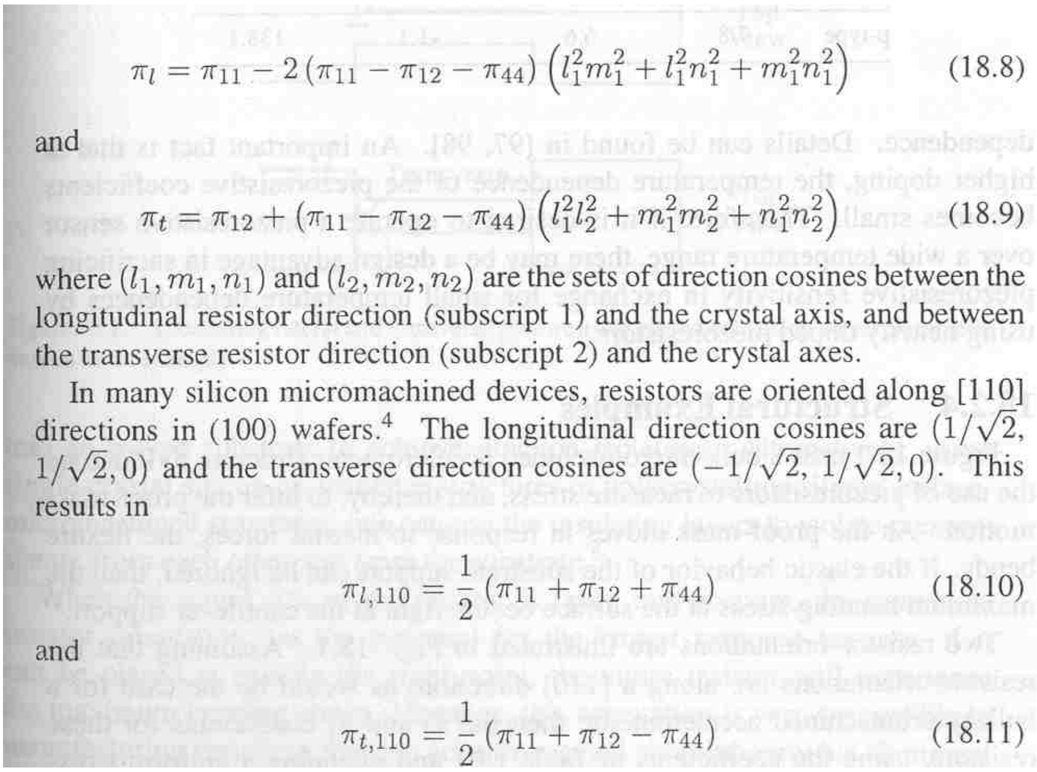


Table 7.9 | Piezoresistive coefficients of p-type silicon piezoresistors in various directions

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

Source: Brysek et al. [1991].

- Relationship between (π_l, π_t) and (π_{11}, π_{12}, π_{44}) [Senturia, 2001]



$$\pi_l = \pi_{11} - 2(\pi_{11} - \pi_{12} - \pi_{44})\left(l_1^2 m_1^2 + l_1^2 n_1^2 + m_1^2 n_1^2\right) \qquad (18.8)$$

and

$$\pi_t = \pi_{12} + (\pi_{11} - \pi_{12} - \pi_{44})\left(l_1^2 l_2^2 + m_1^2 m_2^2 + n_1^2 n_2^2\right) \qquad (18.9)$$

where (l_1, m_1, n_1) and (l_2, m_2, n_2) are the sets of direction cosines between the longitudinal resistor direction (subscript 1) and the crystal axis, and between the transverse resistor direction (subscript 2) and the crystal axes.

In many silicon micromachined devices, resistors are oriented along [110] directions in (100) wafers.[4] The longitudinal direction cosines are $(1/\sqrt{2}, 1/\sqrt{2}, 0)$ and the transverse direction cosines are $(-1/\sqrt{2}, 1/\sqrt{2}, 0)$. This results in

$$\pi_{l,110} = \frac{1}{2}(\pi_{11} + \pi_{12} + \pi_{44}) \qquad (18.10)$$

and

$$\pi_{t,110} = \frac{1}{2}(\pi_{11} + \pi_{12} - \pi_{44}) \qquad (18.11)$$

7.7 Gallium Arsenide (GaAs, 砷化鎵)

- GaAs
  - A compound semiconductor
  - Advantages
    - A prime candidate material for photonic device due to its high mobility of electrons (7 times higher than silicon, see Table 7.11)
      → easier for electric current to flow in the material
    - Superior thermal insulator with excellent dimensional stability at high temperature

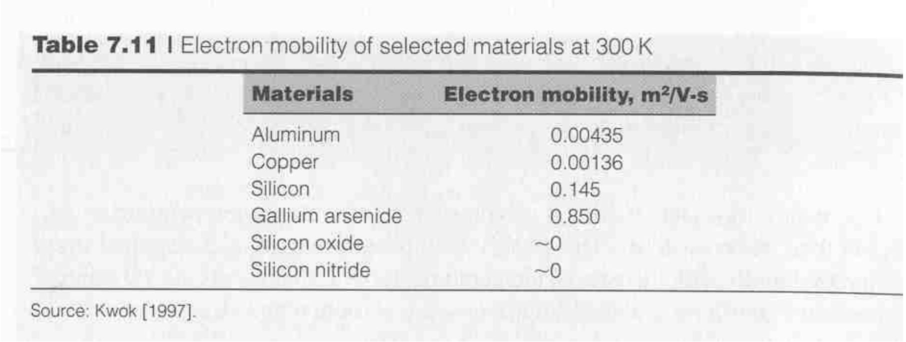


Table 7.11 | Electron mobility of selected materials at 300 K

Materials	Electron mobility, $m^2/V\text{-}s$
Aluminum	0.00435
Copper	0.00136
Silicon	0.145
Gallium arsenide	0.850
Silicon oxide	~0
Silicon nitride	~0

Source: Kwok [1997].

- Disadvantages
  - ➢ More difficult to process than silicon
  - ➢ Low yield strength (one-third of that of silicon)
  - ➢ More expensive than silicon due to its low use
- Comparison of GaAs and silicon

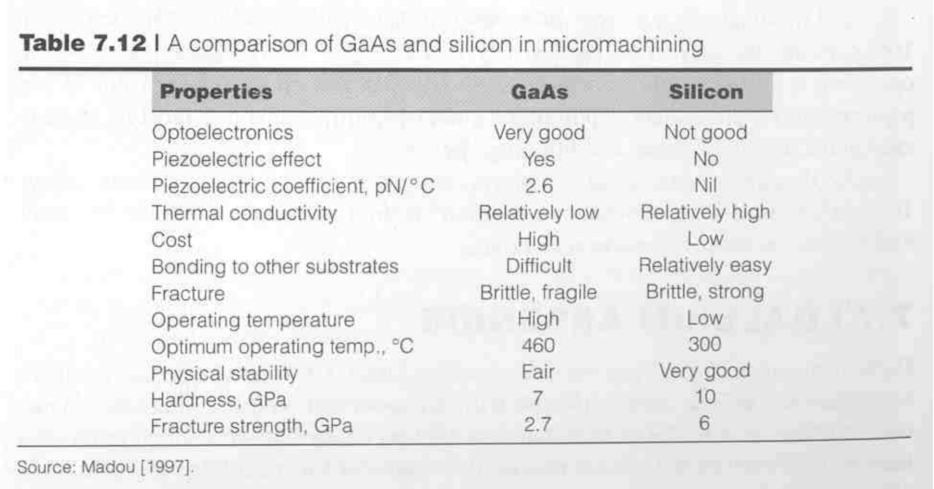


Table 7.12 | A comparison of GaAs and silicon in micromachining

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 (石英)

- Quartz
  - A compound of SiO_2
  - Unit cell in the shape of tetrahedron (四面體)
  - Orientation: (Senturia, 2001)
    - ➢ Not based on miller indices
    - ➢ Some basic orientations, such as *X*-cut and *Z*-cut quartz, refer to the crystalline axes normal to the plane of the wafer.
    - ➢ However, some others, such as *AT*-cut quartz, refer to off-axis orientations that are selected for specific temperature insensitivities of their piezoelectric or mechanical properties.
  - An ideal material for sensor because of its near absolute thermal dimensional

stability

- A desirable material in microfluidics applications in biomedical analyses
  - ➢ Inexpensive
  - ➢ Work well in electrophoretic (電泳) fluid transportation due to its excellent electric insulation (絕緣) properties
  - ➢ Transparent to ultraviolet light which is good for the purpose of species detection
- Hard to machine
  - ➢ Could use “diamond cutting” or “ultrasonic cutting”
  - ➢ Can be etched chemically by HF/NH_4F into the desired shape
- More dimensionally stable than silicon
- More flexibility in geometry than silicon

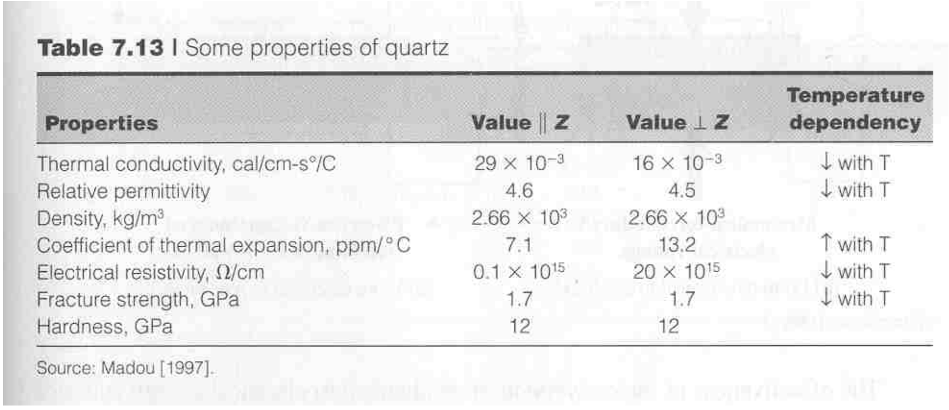


Table 7.13 | Some properties of quartz

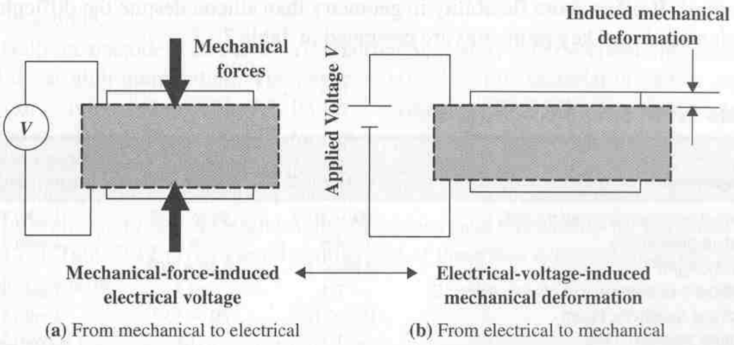
Properties	**Value $\parallel z$**	**Value $\perp z$**	**Temperature dependency**
Thermal conductivity, cal/cm-s°/C	29×10^{-3}	16×10^{-3}	↓ with T
Relative permittivity	4.6	4.5	↓ with T
Density, kg/m^3	2.66×10^3	2.66×10^3	
Coefficient of thermal expansion, ppm/°C	7.1	13.2	↑ with T
Electrical resistivity, 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

- ● Piezoelectric crystals
  - Piezoelectric effect:
    - ➢ Produce a voltage when subjected to an applied force
    - ➢ The application of voltage to the crystal can change its shape.

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



(a) From mechanical to electrical

(b) From electrical to mechanical

(From Kasap [1997].)

- Natural crystals: quartz (石英), tourmaline (電氣石), and sodium (鈉) potassium (鉀) tartrate (酒石酸鹽[酯])
- Synthesized crystals: Rochelle salt, barium titanate, and lead zirconate titanate (PZT)
- Its structure should have no center of symmetry
  - ➢ The applied stress will alter the separation between the positive and negative charge sites in an elementary cell, leading to a net polarization at the crystal surface.

    → result in an electric field with voltage potential
- Applications
  - ➢ High voltage generation via the application of high compressive stress

    → can be used as an impact detonation (引爆) device.

    → can be used to send signals for depth detection in a sonar (聲納) system
  - ➢ In MEMS: used as actuators (see Chapter 2) and dynamic signal transducers for pressure sensors and accelerometers.
  - ➢ Used in pumping mechanisms for microfluidic flows (Chapters 5 & 6) as well as for inkjet printer heads.

● Effectiveness of the conversion of mechanical to electrical energy and vice versa can be assessed by the electromechanical conversion factor K:

$$K^2 = \frac{\text{output of mechanical engergy}}{\text{input of electrical engergy}} \tag{7.9a}$$

or

$$K^2 = \frac{\text{output of electrical engergy}}{\text{input of mechanical engergy}} \tag{7.9b}$$

- The electric field produced by stress

  $$V = f\sigma \tag{7.10}$$

  where V: generated electric field in V/m; f: constant coefficient; σ: applied stress in pascals (Pa)
- The mechanical strain produced by the electric field

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

  where ε: induced strain; V: applied electric field in V/m; d: piezoelectric coefficient (see Table 7.14)

- Relation between f and d:

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

where E: the Young's modulus

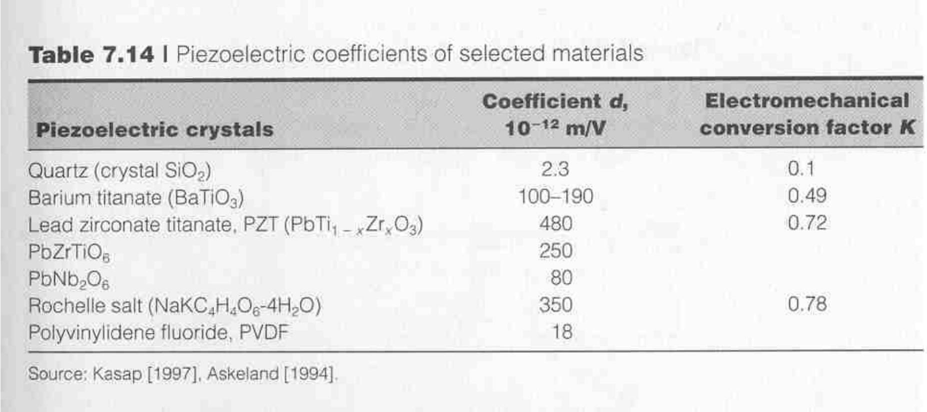


Table 7.14 | Piezoelectric coefficients of selected materials

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 ($PbTi_{1-x}Zr_xO_3$)	480	0.72
$PbZrTiO_6$	250	
$PbNb_2O_6$	80	
Rochelle salt ($NaKC_4H_4O_6$-$4H_2O$)	350	0.78
Polyvinylidene fluoride, PVDF	18	

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

7.10 Polymers

- Polymers
  - Include diverse materials such as plastics, adhesives, Plexiglas (普列克斯玻璃: 用以製造飛機座艙罩等的丙烯酸樹脂的商品名), and Lucite (路賽特: 一種透明或半透明的合成樹脂,發螢光,用於反射鏡、飛機窗子等)
  - Become increasingly popular materials for MEMS and Microsystems
  - Examples in MEMS and microsystems:
    - ➢ Plastic cards approximately 150 mm wide containing 1000 microchannels for microfluidic electrophoretic systems by the biomedical industry (Lipman, 1999)
    - ➢ Epoxy resins (環氧樹脂) and adhesives (黏著劑) such as silicone rubber (矽氣橡膠 - 在高溫和低溫下都能保持彈性) used in packing
  - Made up of long chains of organic (有機體[物]的, mainly hydrocarbon) molecules
  - Characteristics:
    - ➢ Low mechanical strength
    - ➢ Low melting point
    - ➢ Poor electric conductivity
  - Thermoplastics and thermosets: 2 groups of common polymers
    - ➢ Thermoplastics: easily formed to the desired shape
    - ➢ Thermosets: have better mechanical strength and temperature resistance up to 350℃

7.10.1 Polymer as Industrial Materials

- Applications:
  - Used as insulators, sheathing ([電纜的]護皮), capacitor films in electric

devices, and die pads in integrated circuits.

- Advantages
  - ➢ 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
  - ➢ Great variety

7.10.2 Polymers for MEMS and Microsystems

- Applications:

1. Photoresist (光阻) polymers: used as masks for creating desired patterns on substrates by photolithography (微影).
2. Photoresist polymers: used to produce the prime mold in the LIGA process.
3. Conductive polymers: used as organic substrates.
4. Ferroelectric (鐵電性的) polymers (which behave like piezoelectric crystals): used as a source of actuation in microdevices such as those for micropumping (Sec.5.6.3).
5. Thin Langmuir-Blodgett (LB) film: used for miltilayer microstructures
6. Used as a coating substances for capillary tubes to facilitate electro-osmotic flow in microfluidics (Sec. 3.8.2)
7. Thin polymer films: used as electric insulators in microdevices and asa dielectric substances in microcapacitors.
8. Used for electromagnetic interference (EMI) and radio-frequency interference (RFI, 射頻干擾) shielding (遮蔽) in Microsystems.
9. Used for the encapsulation (密封)of microsensors and packaging of other microsystems.

7.10.3 Conductive Polymers

- For some application, polymers have to be made electrically conductive.
  - By nature, polymers: poor electric conductors (Table 7.15).
  - Polymers can be made electrically conductive by the following 3 methods:

1. Pyrolysis:
   - A pyropolymer based on phthalonitrile resin: by adding an amine (胺－ 氨分子中的氫原子被烷基取代而形成的鹼式化合物) heated above 600℃

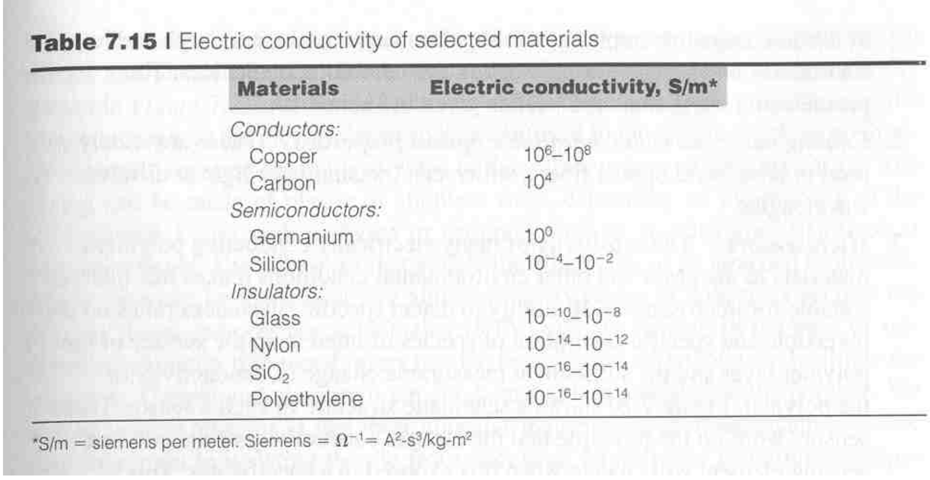


Table 7.15 I Electric conductivity of selected materials

Materials	Electric conductivity, S/m*
Conductors:	
Copper	10^6–10^8
Carbon	10^4
Semiconductors:	
Germanium	10^0
Silicon	10^{-4}–10^{-2}
Insulators:	
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 = $\Omega^{-1} = A^2\text{-}s^3/kg\text{-}m^2$

2. Doping

   Examples:

   - For polyacetylenes (PA): Dopants such as Br_2, I_2, AsF_5, $HClO_4$, and H_2SO_4 to produce p-type polymers, and sodium naphthalide in tetrahydrofuran (THF, 四氫〔1071〕喃: 一種無色液體,用於製造溶劑、尼龍等) for the n-type polymer.
   - For PPP and PPS: see page 265

3. Insertion of Conductive Fibers (纖維)

   A. Incorporate conductive fillers (e.g., carbon, aluminum flakes, stainless steel, gold, and silver fibers) into both thermosetting and thermoplastic polymer structures.

   B. Other inserts include semiconducting fibers (nanometers in length), e.g., silicon and germanium.

7.10.4 The Langmuir-Blodgett (LB) Film

- LB film
  - made by a special process (LB process) to produce thin polymer films
  - involves spreading volatile solvent (溶劑) over surface-active materials
  - The LB process can produce more than a single monolayer structure (i.e., create a multi-layer structure).

    → regarded as an alternative micromanufacturing technique.

- Applications:

1. Ferroelectric polymer thin films
   - Such as polyvinylidene fluoride (PVDF, 聚偏二乙烯的氟化物)
   - Applications: (a) sound transducers in air and water, (b) tactile (觸覺的)

sensors, (c) biomedical applications (such as I. Tissue-compatible implants, II. cardiopulmonary (心肺的) sensors, and III. implantable transducers and sensors for prosthetics (修復術) and rehabilitation (康復) devices)

- See Table 7.14 for the piezoelectric coefficient of PVDF.

2. Coating materials with controllable optical properties

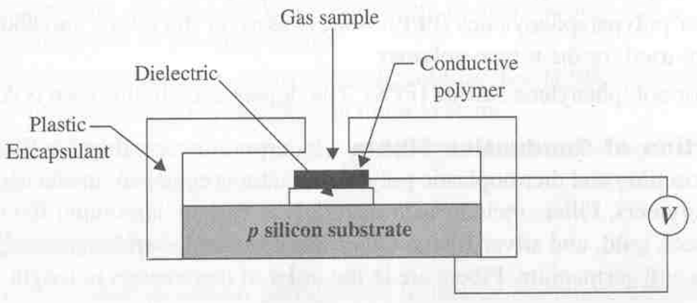
- widely used in broadband optical fibers

3. Microsensors

Principle of Fig. 7.20:

- The electric conductivity of the polymer sensing element will change when it is exposed to a specific gas.

Figure 7.20 | Microsensor using polymers.



7.11 Packaging Materials

- Distinction between the IC packaging and the microsystems packaging:
  - For IC: to protect from the hostile operating environment.
  - For microsystems: in addition to protection, it is required to be in contact with the media that are sources of action.

- Materials for microsystem packaging:
  - Include those for IC packaging:
    (a) wires made of noble metals at silicon die level,
    (b) metal layers for lead wires,
    (c) solders (焊劑) for die/constraint base attachments, etc.
  - Also include metal and plastics.

- Consider the microsystem packaging in Fig. 7.21:
  (a) Use aluminum or gold metal films as ohmic contacts to the piezoresistors that are diffused in the silicon diaphragm.

(b) Similar materials: used for the lead wires to the interconnects outside the casing.

(c) Casing: made of plastic or stainless steel

(d) Constrain base: made of glass (e.g., Pyrex [派萊克斯耐熱玻璃]) or ceramics (e.g., alumina [明礬])

(e) Adhesives that attach the silicon die to the constraint base: can be

  i) tin-lead (錫鉛) solder alloys (thin metal layers needs to be sputtered at the joints to facilitate the solderingP;

  ii) epoxy resins (環氧樹脂)

  iii) or Room-temperature vulcanizing (RTV) silicone rubber.

Figure 7.21 | A typical packaged micropressure sensor.