13. Actuators
- Smart material-based

Smart material-based actuators

- Actuators using materials that respond to a particular stimulus from the environment (upon application of external driving forces) in a unique manner (with a change in their properties)
- Input → material → output

- Electric input – piezoelectric material
- Thermal input – shape memory alloy
- Magnetic input – magnetostrictive material

Piezoelectric actuators

(+) Small displacement but strong force

(+) Bi-directional actuation

(+) Simple design

(-) No DC response

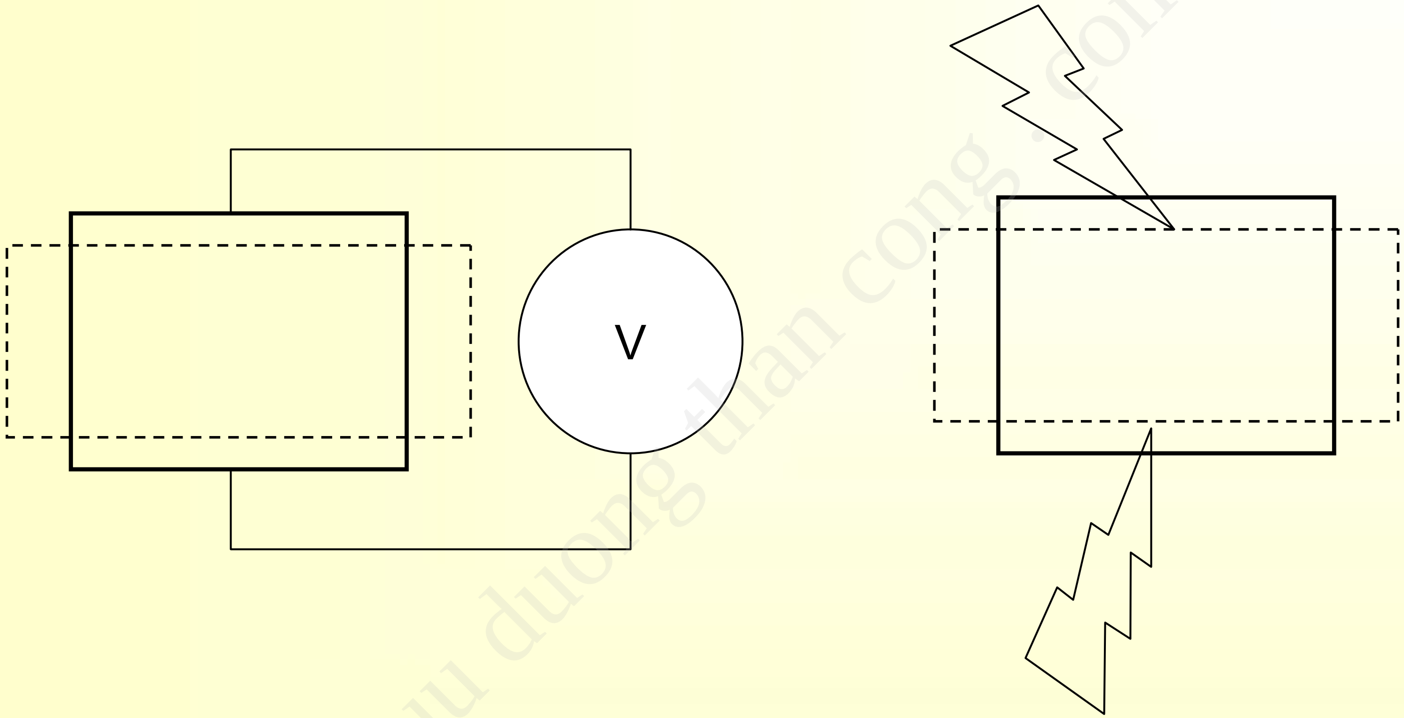
(-) Limited low frequency response

(-) High voltage

(-) Needs certain volume to be useful

Piezoelectricity

- A phenomenon in which a mechanical stress on a material produces an electrical polarization and reciprocally, an applied field produces mechanical strain
- For a crystal to exhibit the piezoelectric effect, its structure should have no center of symmetry
- A stress applied will alter the separation between the positive and the negative charge sites in each elementary cell, leading to a net polarization at the crystal surface


V

- Basic material system

PZT ($PbZr_xTi_{1-x}O_3$)

BaTiO3

Quartz (crystal SiO2)

Zinc oxide

PVDF (Plyvinylidene fluoride)

- Electromechanical conversion factor, K

$$K^2 = \frac{\text{output of mechanical energy}}{\text{input of electrical energy}}$$

$$K^2 = \frac{\text{output of electrical energy}}{\text{input of mechanical energy}}$$

- Piezoelectric coefficient, d

$\varepsilon = d\mathcal{E}$

Induced Strain = Piezo. Coeff * Applied field (V/m)

Table 7.14 | Piezoelectric coefficients of selected materials

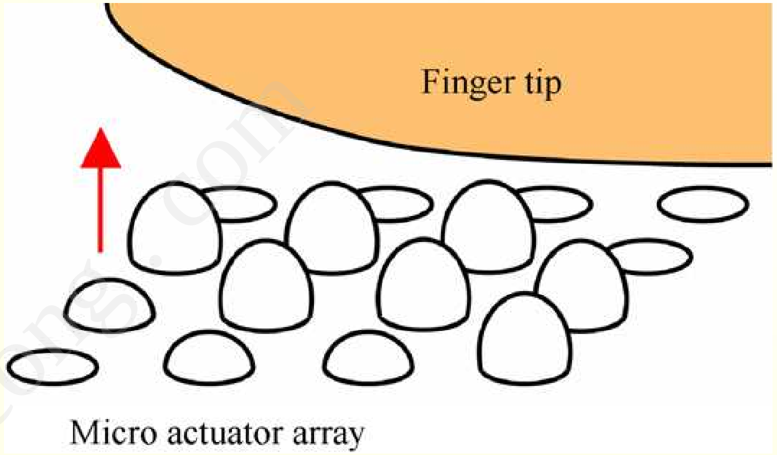
Piezoelectric crystals	Coefficient d, 10^{-12} m/V	Electromechanical conversion factor K
Quartz (crystal SiO_2)	2.3	0.1
Barium titanate ($BaTiO_3$)	100–190	0.49
Lead zirconate titanate, PZT ($PbTi_{1-x}Zr_xO_3$)	480	0.72
$PbZrTiO_6$	250	
$PbNb_2O_6$	80	
Rochelle salt ($NaKC_4H_4O_6$-$4H_2O$)	350	0.78
Polyvinylidene fluoride, PVDF	18	

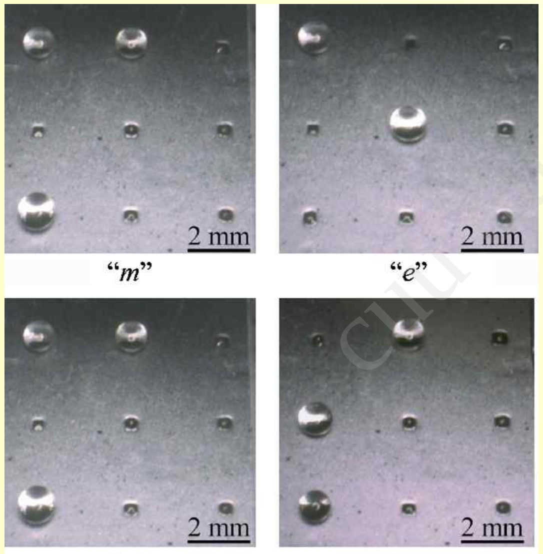
Source: Kasap [1997], Askeland [1994].

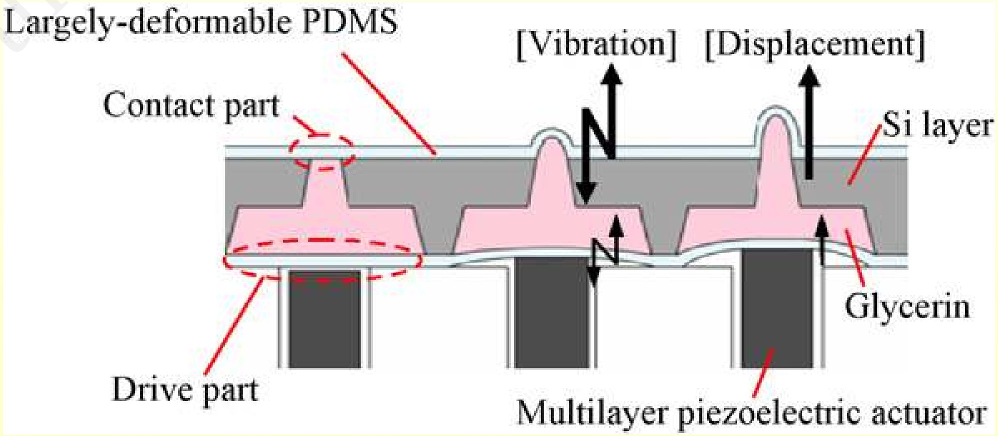
T-R. Hsu, "MEMS and Microsystems", McGraw-Hill, 2001

Tactile display

T. Ninimiya, Y. Okayama, Y. Matsumoto, X. Arouette, K. Osawa and N. Miki, “MEMS-based hydraulic displacement amplification mechanism with completely encapsulated liquid”, Sensors and Actuators A (2009)
0-1 kHz, 100 um displacement







Shape memory alloy actuator

(+) High power/volume ~ 10^6-10^7 J/m^3
(+) Large force-displacement
(+) Low driving voltage
(+) Simple design
(+) Durability
(+) Bio-compatibility for biomedical applications
(-) Composition-sensitive
(-) Difficult fabrication process
(-) Slow response
(-) Heat

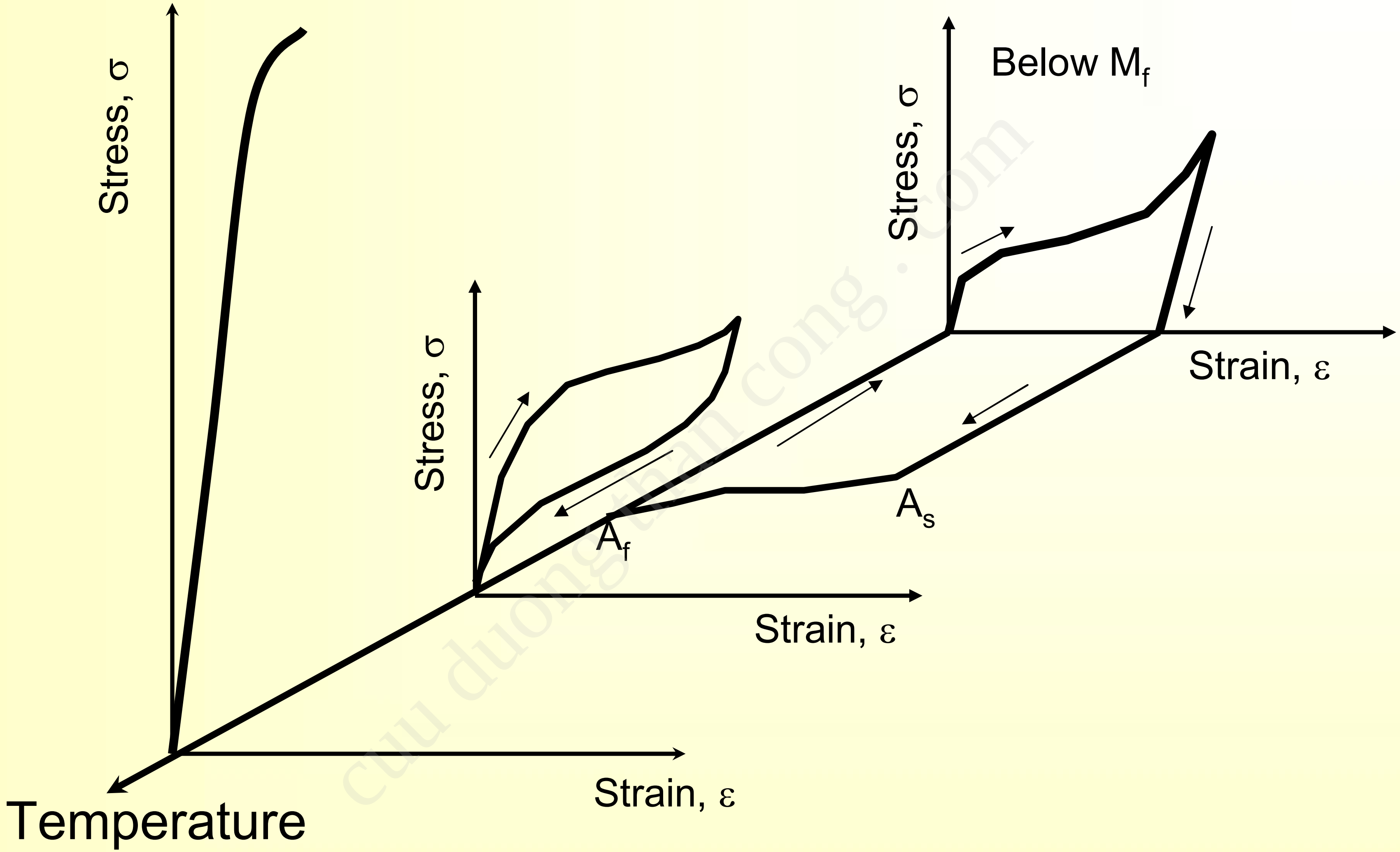
Shape memory effect

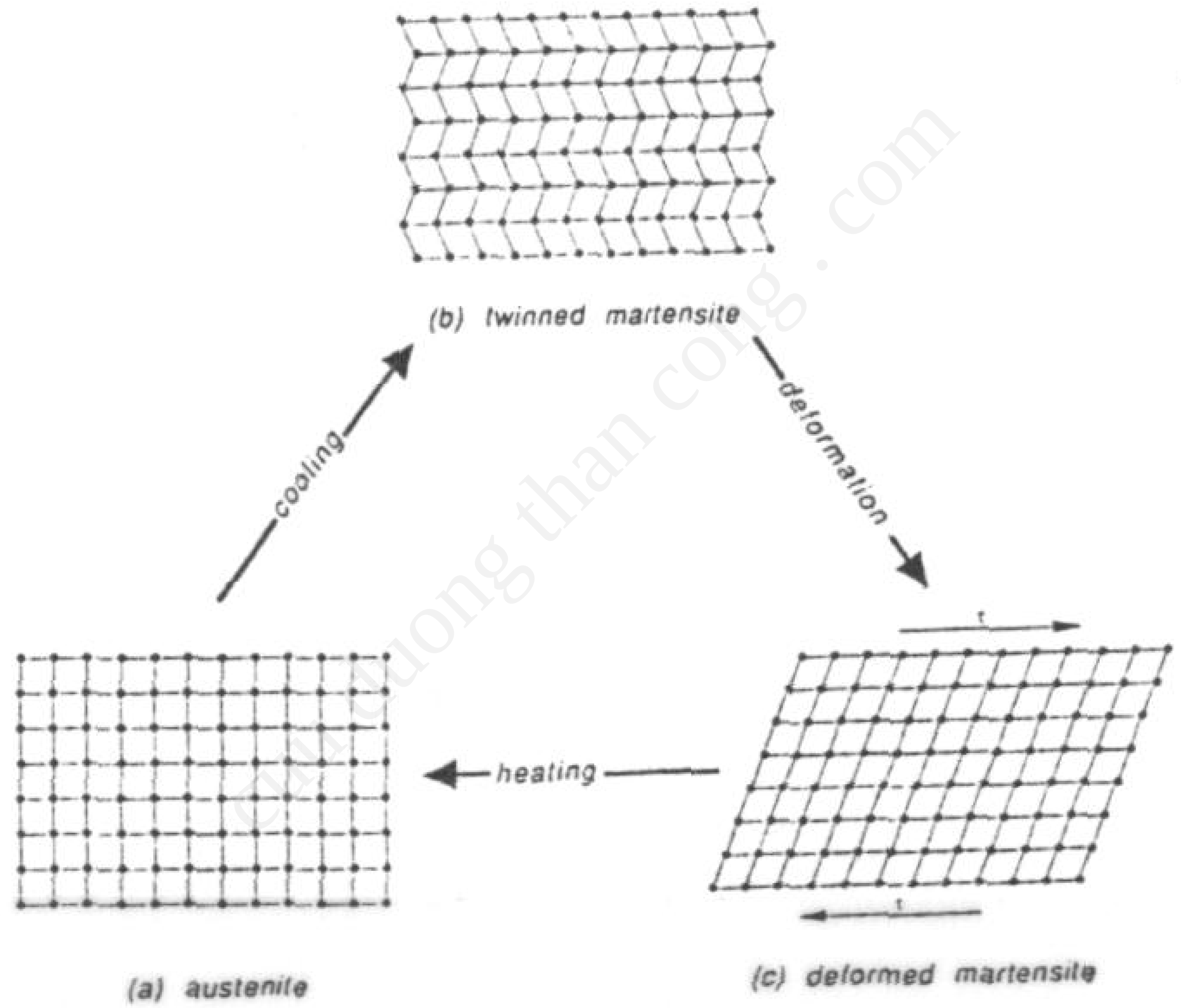
- Use martensite-austenite phase transformation upon heating or cooling
- Use twinning not slip for deformation
- Shape recovered upon heating
- The temperature at which the alloy remembers its high temperature form when heated can be adjusted by slight changes in alloy composition and through heat treatment

shape memory fabric

Superelasticity

- Deformation slightly above the transition temperature
- Stress-induced martensitic transformation
- Rubber-like behavior


Stress, σ
Temperature
Strain, ε
Stress, σ
Strain, ε
A_f
A_s
Below M_f
Stress, σ
Strain, ε


(b) twinned martensite
deformation
t
t
(c) deformed martensite
heating
(a) austenite
cooling

- Basic material system

Ni-Ti-X X=Pt, Pd, Au, Rh, Hf, Zr etc.

Ni-Al

Cu-Al-Ni

Ni-Mn

Cu-Zr

- Fabrication

  Sputtering

  Lift-off

  Heat treatment is critical:

  500-800°C 10min-1hr

❑ SMA valve

Size: 6x6x2 mm

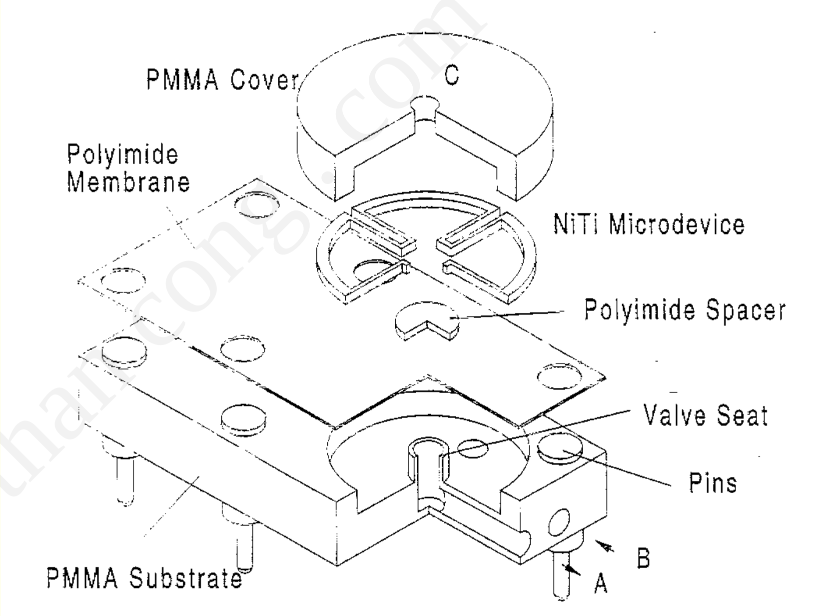
Operating under
gas flow 1600sccm
at 1200hPa

Work output 35 μNm

Power < 450mW

Response time
0.5-1.2 sec (closing)
1-2 sec (opening)

Af = 86°C



M. Kohl, K. D. Skroban and S. Miyazaki, "Development of stress-optimized shape memory microvalves", Sensors and Actuators 72(1999) 243-250

Considerations

- Design is often limited by fabrication method
- Integrated or hybrid?
- Displacement
- Frequency and response time
- Power consumption
- Working environment