After Poling, application of a +V or a -V will result in "+" or "-" dimensional change → actuator

OR → mechanical compressive or tensile strain will produce a corresponding voltage across the crystal → sensor

→ U too large or T too high → can depolarize crystal

→ \( \vec{D} = \vec{P} + \vec{\varepsilon} \vec{E} \) → Describing equation

\( \vec{D} \) = electric flux density, \( \vec{P} \) = electrical polarization
\( \vec{\varepsilon} \) = piezoelectric coefficient matrix
\( \vec{T} \) = applied mechanical stress
\( \varepsilon \) = electrical permittivity matrix
\( \vec{E} \) = electric field

Example Piezoelectric Materials used in MEMs

1. Quartz → SiO₂ → bulk material
2. ZnO → Zinc Oxide → thin film
3. PZT → Pb₃Zr₃TaO₁₂ → lead zirconate titanate → bulk or thin film
4. Others

→ The use of Piezoelectric materials is generally not as standard a fabrication process as Si based microfabrication.
→ Often not compatible with IC fabrication processes

→ Since \( |E_\text{piezo}| > |E_\text{air}| \): piezo based vibration energy scavenging devices are more efficient than electrostatic energy scavenging devices
1. Other types of MEMS actuators
   a. Magnetic MEMS Actuators
       → Sometimes used, however, electrostatic forces scale better than magnetic forces as size is reduced to the micro scale.

   Types
   1) External magnetic field causes microstructure actuation

      no magnetic field
      \[ \text{applied magnetic field} \]

      \[
      \begin{align*}
      \text{print mass is made of} & \quad \text{or coated with a} \\
      \text{ferromagnetic material} & \quad \text{such as iron, nickel, cobalt, etc.}
      \end{align*}
      \]

   2) Internally generated magnetic fields
      → Realize coiled structures in MEMS technology
      → Challenging but possible
      → Force ∝ Current ⇒ High power required, compared to electrostatic

   3) MEMS structure with microfabricated magnets/attached magnets
      → Can be actuated using external ferromagnetic material in close proximity, externally generated magnetic field or on-chip MEMS electromagnet
b. Shape Memory Alloys (SMA)

- A material that has a rigid state above a certain temperature (Tc) called the Austenite phase, and a pliable state called the Martensite phase below Tc.

- Whatever shape the material initially had in the Austenite phase, it will forcefully return to that shape when the temperature rises above Tc.

- Tc is the phase transition temperature.

Ex: Nitinol → a commonly used MEMS SMA material

- Up to a 5% strain during the Martensite phase without losing the SMA properties.
- Tc is tailorable between -100°C to +100°C.
- As T increases to > Tc, pressure produced can be as high as 100,000 psi to return the material to the original shape.

- Macroscale application → replacing explosive bolts
- Nitinol → Nickel Titanium Naval Ordnance Laboratory → place where it was discovered in 1962.
c. Other actuators fabricated in MEMS technology

1. Steam Engine
2. Internal Combustion
3. Solid Rocket

→ applications: probably none

d. Microfluidic Actuation

1. Thermal Pump

consider the device below

- a gas filled sealed chamber
- a Joule heater (on → gas heats and expands)
- membrane < deflects out when gas heats, deflects in when gas cools >

4. chamber where fluid being pumped flows through

5. input flapper valve < closes when gas in 1 is Joule heated >
6. output flapper valve < opens when gas in 1 is Joule heated >

→ one application is in PCB fluidic MEMS devices
(2) Flow FET

→ based on electro-osmotic flow

Consider a micro channel:

Charge builds up on μ-channel wall
- negatively charged ions are attracted toward the positively charged μ-channel wall

Add electrodes: → "Source" and "Drain" electrodes

The bias voltage between the electrodes (~100V) causes the negatively charged ions to move toward the + voltage electrode.
These moving ions push the fluid with them, → flow
→ Add a third electrode on opposite wall to modulate this effect → acts like a MOSFET gate electrode

This pump behaves similar to a MOSFET where "I₀" is the flowing fluid. Hence the name "FlowFET"
Single Piston Steam Engine (Sandia)
Wankel Engine (U.C. Berkeley)
MEMS Rocket Engine (U.C. Berkeley)
Thermal Pump (Univ. of Rostock)

Schematically Cross-Section of thermally driven Micro Pump

- Inlet (Ø 1 mm)
- Actuator chamber (air) (Ø 10 mm)
- Heating wire or thin film heater (Constantan® Ø 70μm)
- Outlet (Ø 1 mm)
- Copper (70 μm)
- Membrane (8 μm Kapton®)
- Fr4 (0.8 mm)
- Inlet valve Ø 5 mm
- Pump chamber (Ø 10 mm)
- Outlet valve Ø 5 mm