After Poling, application of a +V or a −V will result in "+" or "−" dimensional change → <u>actuator</u>

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

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

→ $\vec{D} = \vec{d}\vec{T} + \vec{\varepsilon}\vec{E}$ → Describing equation

$\vec{D}$ ≡ electric flux density {electrical Polarization}

$\vec{d}$ ≡ piezoelectric coefficient matrix

$\vec{T}$ ≡ applied mechanical stress

$\vec{\varepsilon}$ ≡ electrical permittivity matrix

$\vec{E}$ ≡ electric field

<u>Example Piezoelectric Materials used in MEMS</u>

(1) Quartz → SiO_2 → bulk material

(2) ZnO → zinc oxide → thin film

(3) PZT → $PbZrTiO_3$ → 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 $\varepsilon|_{piezo} > \varepsilon|_{air}$: piezo based vibration energy scavenging devices are more efficient than electrostatic energy scavenging devices

1. Other types of MEMS actuators

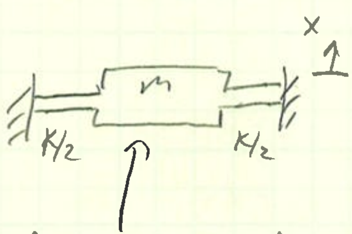
a. Magnetic MEMS Actuators

→ sometimes used, however electrostatic forces scale better than magnetic forces as size is reduced to the micro scale

Types

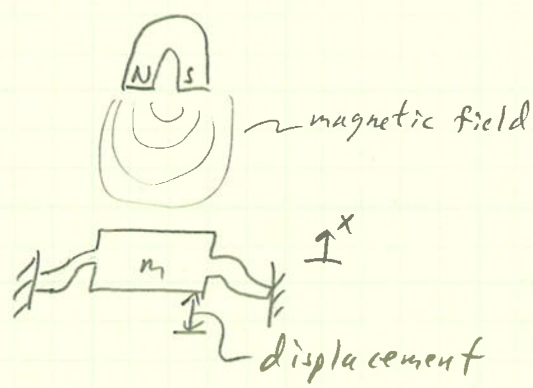
① External magnetic field causes microstructure actuation

no magnetic field



proof mass is made of or coated with a ferromagnetic material such as iron, nickel, cobalt, etc.

applied magnetic field



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 (T_c) called the Austenite phase, and a pliable state called the Martensite phase below T_c

→ whatever shape the material initially had in the Austenite phase, it will forcefully return to that shape when the temperature rises above T_c

→ T_c 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

→ T_c is tailorable between $-100°C$ to $+100°C$

→ as T increases to $> T_c$ → 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

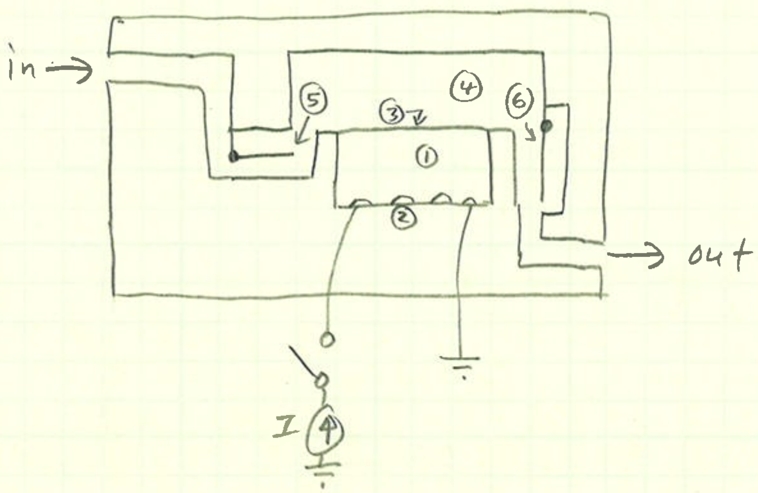
③ Solid Rocket

→ appilcations: probably none

d. Microfluidic Actuation

① Thermal Pump

consider the device below



① → a gas filled sealed chamber

② → a Joule heater (on → gas heats and expands)

③ → 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)

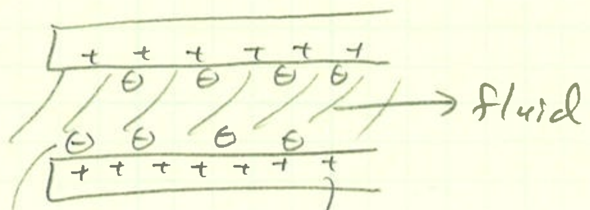
⑥ → output flapper valve (opens when gas in ① is Joule heated)

→ one application is in PCB fluidic MEMS devices

② Flow FET

→ based on electro-osmotic flow

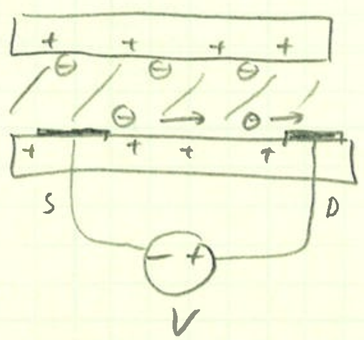
consider a micro channel ↴



charge builds up on μchannel wall

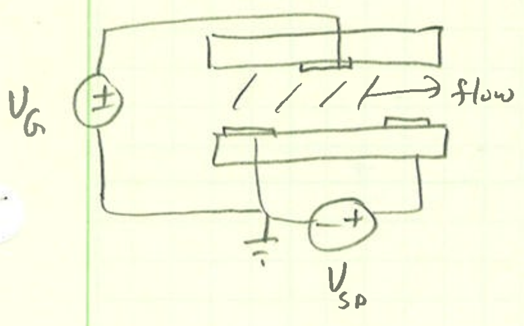
negatively charged ions are attracted toward the positively charged μchannel wall

add electodes: → "Source" and "Drain" electrodes



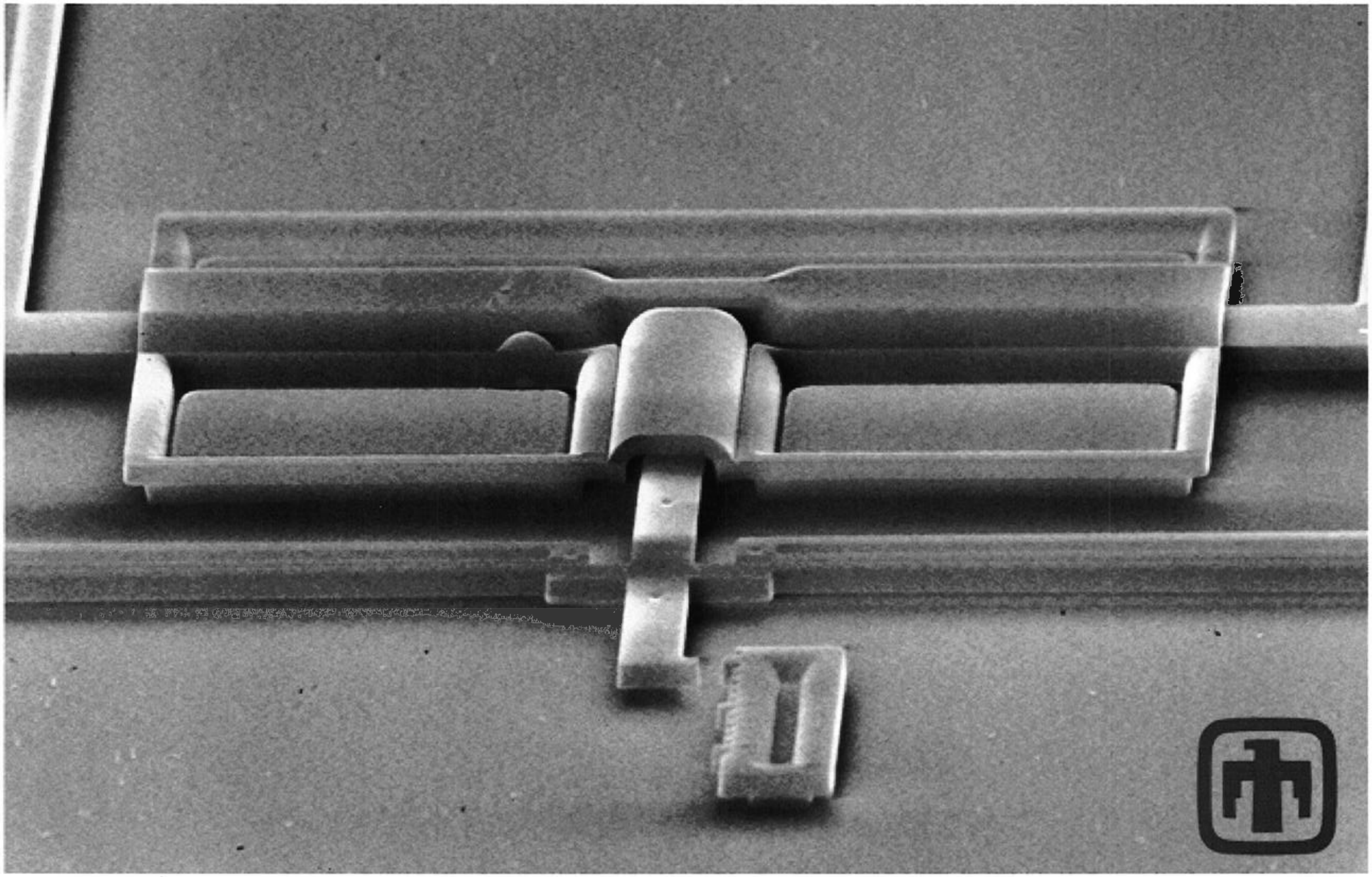
The bias voltage between the electrodes (~100V) causes the negatively charged ions to move toward the +Voltage electrode. These moving ions push the fluid with them → flow

→ Add a third electode on opposite wall to modulate this effect → acts like a MOSFET gate electrode

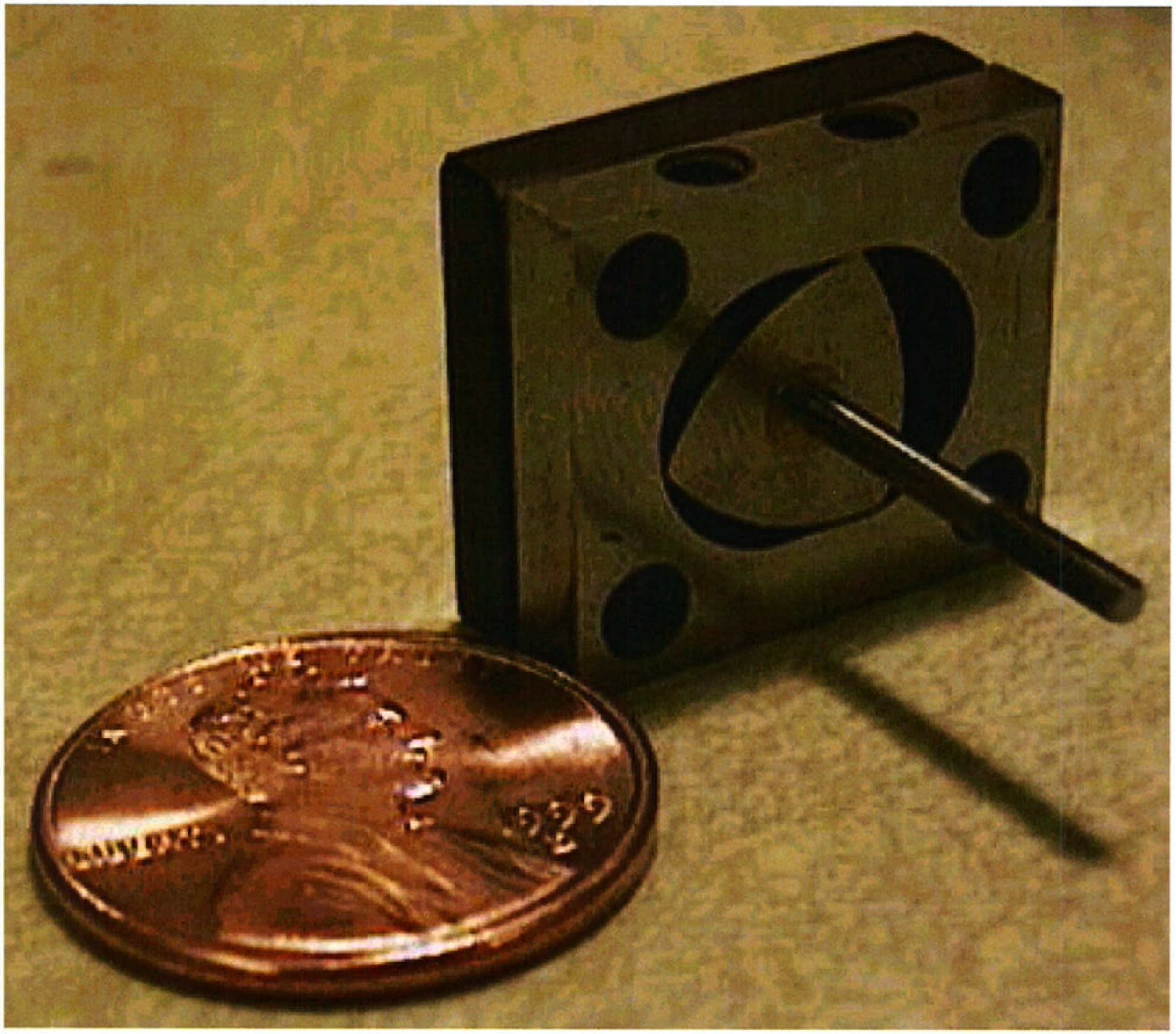


→ This pump behaves similar to a MOSFET where "I_D" is the flowing fluid. Hence the name "FlowFET"

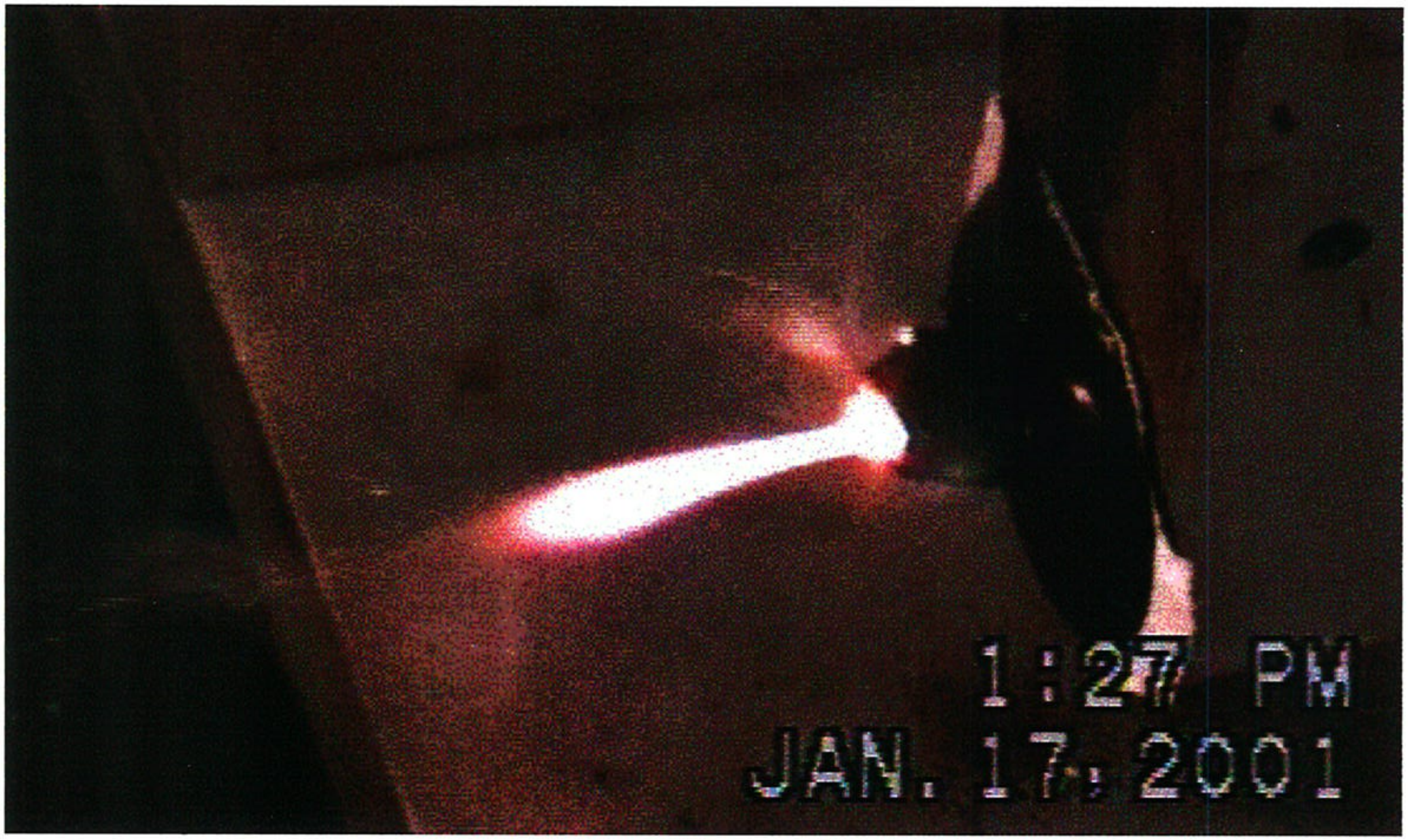
Single Piston Steam Engine (Sandia)



Wankel Engine (U.C. Berkeley)



MEMS Rocket Engine (U.C. Berkeley)



Thermal Pump (Univ. of Rostock)