MEMS
and
Nanotechnology
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The Beginning

In Dec. 1959 Richard Feynman offered a prize of $1,000.

Challenge: build an electrical motor, each side smaller than
\[
\frac{1}{64} \text{in} \approx 0.397 \text{mm}
\]
electrical motor by William McLellan

diameter: 381μm

tools used for assembly:

- microscope
- sharpened tooth pick
- hairs of a fine artist's brush
1. introduction

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What is MEMS?

MEMS - microelectromechanical systems

transformation of energy:

- electricity
- light
- thermal energy

→ mechanical motion

MEMS mainly move by elastic deformation of their flexible components.
What is MEMS?

spider mite (length: approx. 0.5mm)

What is NEMS?

NEMS - nanoelectromechanical systems

• similar to MEMS but smaller (nanoscale)
• future prospects: ability to measure small displacements and forces at a molecular scale

The border between MEMS and NEMS can hardly be defined: 500nm or 0.5μm?
It is possible to create structures with only several nanometers in size, BUT:

- nanoscale cantilevers/beams: a considerable big number of atoms are surface atoms
- interference with surrounding molecules
- additional physical effects have to be considered (e.g. increased influence of adhesion)

⇒ just scaling down MEMS layouts does not work!
problems with NEMS-technology

some examples:

• NEMS can respond to masses of single atoms: sensors could respond to impacts of molecules

• measurement of small deflection/forces also means small signals: difficulty to tell the signals apart from the noise

• adhesion of pieces that operate as capacitive electrodes could induce short circuits
problems with NEMS-technology

- effects, that are irrelevant to micro devices, have to be considered for nano devices
- new design approaches have to be found
- production and packaging have to take place in an extremely clean environment
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   3.1. thermal transduction
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thermal transduction

\[ \Delta l = \alpha \cdot l \cdot \Delta T \]

block force:
\[ F_b = E \cdot A \cdot \alpha \cdot \Delta T \]

\[ F = F_b \]

\[ \Rightarrow \text{ no displacement} \]
active principles

thermal transduction

vertical motion

moveable

fixed

bent beam actuator

bi-metal actuator
active principles

advantages & disadvantages of thermal transduction

+ large forces/displacements
– large input energies
– low frequencies
electrostatic transduction

parallel plate movement: \( \Delta x \)
comb finger movement: \( \Delta A \)

\[
\Delta U = -Q \frac{x}{\varepsilon \Delta A}
\]

\[
\Delta U = Q \frac{\Delta x}{\varepsilon A}
\]
electrostatic transduction

spring elements

parallel electrodes

comb drives

active principles
active principles

advantages & disadvantages of electrostatic transduction

+ fast response
+ easy integration with CMOS
– small actuation force
active principles

piezo-resistive effect

I + ΔI

V

connect piezo actuator to voltage source

⇒ change in length
**active principles**

**piezo-resistive effect**

Compress or expand piezo sensor

\[ V \Rightarrow potential\ difference \]

\[ F \]

\[ l - \Delta l \]
active principles

piezo-resistive effect in polysilicon

\[
gauge \text{ factor } K = \frac{\Delta R}{\frac{R}{\Delta l}}
\]

thin film of polysilicon (p- or n-doped) isolator (e.g. SiO\(_2\), Si\(_3\)N\(_4\))

cantilever/beam/membrane
piezo-resistive effect in polysilicon

maximum gauge factor

p-doped: $-40$

n-doped: $20$

$N_{A/D} \approx 10^{19} \text{cm}^{-3}$

$T_{\text{CVD}} = 560^\circ\text{C}$

annealing: $1000...1100^\circ\text{C}$
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types of MEMS

- sensors
  - accelerometers
  - gyroscopes

- actuators
  - micromirrors
  - droplet generator
  - microengines
  - micropumps
sensors: accelerometers

- in automotive applications to activate safety systems and to implement vehicle stability systems
- hard disc protection systems
- ...
a simple MEMS accelerometer is designed as followed:
- the proof mass is suspended by one to four silicon beams
- basic design and mechanical equivalent:
sensors: accelerometers

- acceleration causes displacement of the proof mass
- displacement of the proof mass can be measured by strain gauges in the beams or change in capacitance

Diagram:
- Suspension beams with strain gauges
- Proof mass with capacitive electrodes
sensors: accelerometers

depending on the change in each capacitance, the three-dimensional acceleration vector can be derived

vertical acceleration

horizontal acceleration
sensors: gyroscopes

gyroscopes

vibratory gyroscopes: transfer of energy between two vibration modes

vibrating mechanical element: proof mass
Coriolis acceleration

\[ \vec{a}_c = 2 \vec{\omega} \times \vec{v} \]
sensors: gyroscopes

rotation detection by capacitive electrodes under the proof mass

Draper Lab comb drive tuning fork gyroscope
actuators: micromirrors

micromirrors for phase modulation

16 μm
actuators: droplet generator

- nozzle
- membrane
- ink reservoir
- cooling hole
- heating element
actuators: microengines

microengine with electrostatically driven combdrives

actuators: microengines

close-up view on different linkage designs

actuators: microengines

torque: \( M_i = F_i \cdot r \cdot |\sin \varphi_i| \)
actuators: micropumps

micropump with piezo actuators

frequency controlled flow rate
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fabrication

epitaxial growth

• thermal oxidation (SiO$_2$-layers)
• chemical vapour deposition
• thermal evaporation (metallic layers)
• electrolytic deposition
fabrication

chemical vapour deposition (CVD)

e. g. layer of phosphorus-doped silicon

Heated chamber

\[ \text{SiH}_4 + \text{PH}_3 \rightarrow \text{n-doped silicon layer} \]
fabrication

minimum structure width:
- ultraviolet light: 1μm
- e-beam, x-ray: <1μm

etching
- plasma etching,
- KOH-etching (Si),
- HF-etching (SiO$_2$),
- ...

ultraviolet light
- mask
- photo resist
- Si, SiO$_2$
fabrication

**etching**

- isotropic
  - e.g. SiO$_2$ etched by HF

- anisotropic
  - e.g. <100> - Si etched by KOH
  - e.g. plasma etched Si
silicon wet etching (e.g. with KOH)

selective etching rate: \[
\frac{R \{ <100> \text{- crystal plane} \}}{R \{ <111> \text{- crystal plane} \}} = 30 \frac{1}{1}
\]
silicon wet etching (e. g. with KOH)

\[
\text{Si} + 2 \text{OH}^- + 2 \text{H}_2\text{O} \rightarrow \text{SiO}_2(\text{OH})_2^- + \text{H}_2
\]

surface structure of \(<111>\) - silicon

surface structure of \(<100>\) - silicon
reactive ion etching: combines chemical and physical etching

e.g. flour ions react with silicon AND heavy ions impact on the surface

attention: physical etching also attacks the pattern
reactive ion etching
reactive ion etching

Si: \( \text{SiCl}_4, \text{CCl}_4, \text{BCl}_3, \text{SF}_6 \)

\( \text{SiO}_2: \ C_2\text{F}_6, \text{CHF}_3 \)
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problems with the fabrication

contamination

- microscopic contaminations (dust)
- molecular dirt:
  - e. g. oil fog from vacuum pumps
    → adhesion degradation of epitaxial layers
problems with the fabrication

hillocks

KOH-etching: dust particles may result in hillocks
list of references & picture credits

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