Micromachinig and MEMS Devices

Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology.

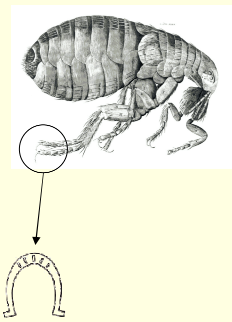
The micromechanical components are fabricated using either selectively etched away parts of the silicon wafer or addition of new structural layers to form the mechanical and electromechanical devices.

MEMS Micro-Machine Technology Solutions

- Microelectromechanical systems (MEMS) are micron-size devices that can sense or manipulate the physical world. MEMS are created using so-called micro machining processes, operations like those used to produce integrated circuit (IC) devices. This allows a mechanical system to be created in the same small area typical of an IC device. Because the manufacturing process is similar to that of producing ICs, MEMS are most typically created on silicon wafers but can employ other substrate types as well. Due to their size, tens of thousands of these devices can be fabricated on a single wafer.
- MEMS technology is **about 25 years old**.

But:

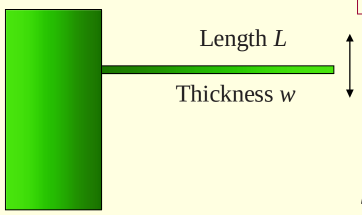
Nikolai S. Leskov (1831-1895): ”Left-Handed Master”
In the story, a group of visiting Englishmen present the Tsar with a tiny mechanical flea (the first MEMS device!). Wanting to better the English achievement, the Tsar asks the Left-Handed Master to create something even more ingenious and of course smaller. The Master rose to the challenge by creating tiny horseshoes on the feet of the mechanical flea.



Benefits of MEMS

• Customers today are demanding smaller, lighter products with more features.
• MEMS are a combination of mechanical and electrical features on a very small scale, are extremely small and can therefore be capable of faster, more precise and more reliable operation than their larger mechanical counterparts.
• The areas where performance / size / cost benefits can be realized using MEMS are almost unlimited.

f is much larger for smaller-size devices,
-> not sensitive to mecahnical vibrations



f : the beam resonance oscillation frequency

$$f = \frac{1}{2\pi}\sqrt{\frac{2Y}{3\rho}}\frac{w}{L^2} = const\cdot\frac{w}{L}\cdot\frac{1}{L}$$

Young's modulus $Y = 1.69{*}10^{11}$ N/m^2 (in the <110> direction)
Shear modulus $G = 5{*}10^{10}$ N/m^2; $\rho = 2.33$ g/cm^3

Typical Device Applications

- **Inertial Measurements -** Accelerometers, gyroscopes, rate sensors, vibration sensors, airbags triggers.
- **Pressure Measurements -** TPMS (Tire Pressure Monitoring System) , disposable blood pressure sensors and various industrial applications.
- **Display Technology -** Optical MEMS in projectors, plasma displays.
- **RF Technology -** Tunable filters, RF switches, antennas, phase shifters, passive components (capacitors, inductors).
- **Chemical Measurements –** Micro-fluidics: Lab-On-Chip devices, DNA test structures, micro-dispensing pumps, hazardous chemical and biological agent detectors

Micromachining Techniques

• Bulk Si Micromachining

Features are etched into the bulk of Si.

Materials: single-crystal Si

• Surface Micromachining

Features are built up from the surface

Materials: poly-crystals, plastics/resists

• 3D Micromachining

Stereolithography
Laser-assisted CVD or etching...

Materials: resists, plastics, thin films.

LIGA

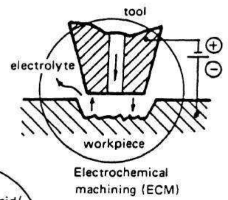
Micromachining Requirements

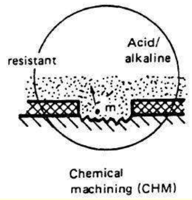
- Dimension control (chemical etching: control, selectivity, etch stop layer)
- Compatibility with IC technology.
- Chemical resistance, mechanical and electrical strength; low mechanical stress; low pin-hole density

Micromachining Tools

-Wet Chemical (Photochemical) Machining and Electrochemical (Including Electroless)

- Photofabrication (S)
- Stereo lithography (A)
- Photochemical milling (S)
- Chemical and electrochemical milling (S)
- Electroplating and electroless plating (A)



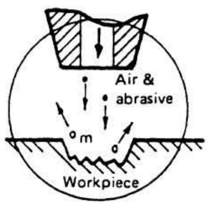


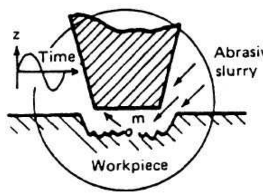
A: additive; S: subtractive

Micromachining Tools

-Mechanical Machining

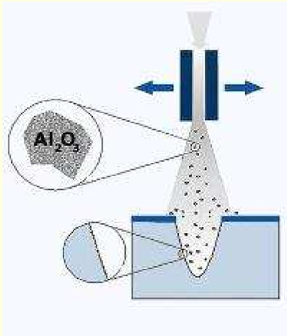
- Ultrasonic machining (S)
- Diamond milling (S)
- Abrasive jet machining (S)





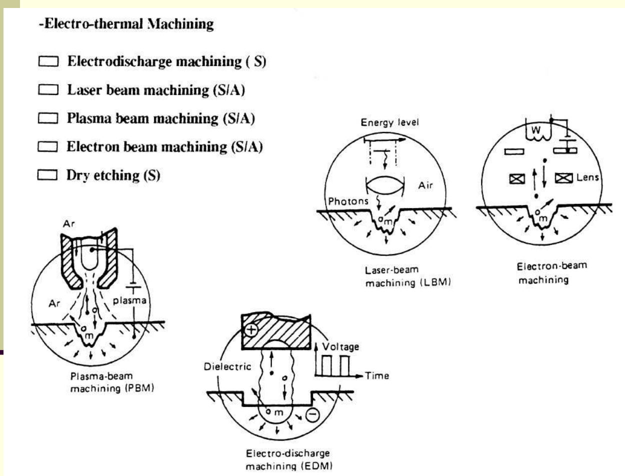
A: additive; S: subtractive

Poweder Blasting



Powderblasting is a flexible, cost-effective and accurate technique for making fluidic channels and interconnections. Because of using a mask, position and channel size accuracy is within 10 µm. There are no limits to the shape of the holes and trenches.

Micromachining Tools



NdYAG pulsed laser for micromachining

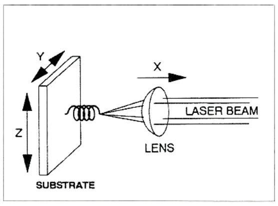
A: additive; S: subtractive

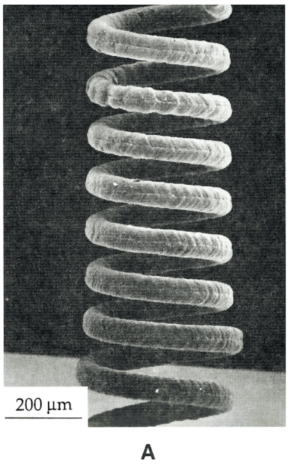
Laser Micromachining in Medicine

Ø 0.02 mm

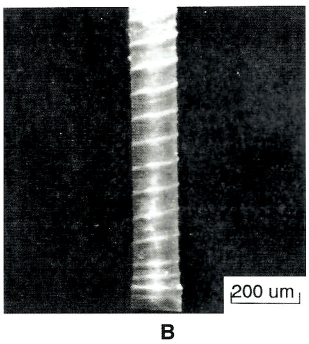
Ø 0.08 mm

Laser-Assisted CVD



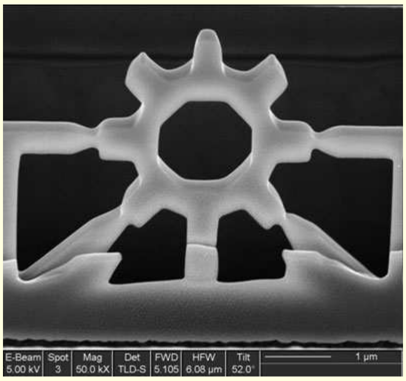


A



B

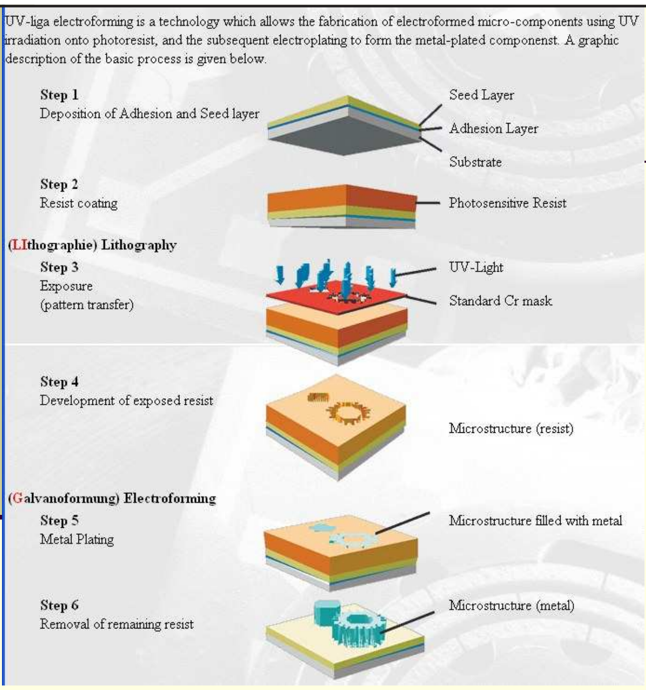
FIB- Processing: CVD and Micro/Nano machining



LIGA

- LIGA stands for X-ray LIthography, Electroforming (German: Galvanoformung), and molding (German: Abformung).
- This technology allows defining high-aspect-ratio structures in nickel. The process consists of exposing a sheet of PMMA bonded to a wafer using X-ray lithography. The PMMA is then developed and the exposed material is removed.
- Nickel is then electroplated up in the open areas of the PMMA. The nickel over-plate is removed by polishing, leaving high-aspect-ratio nickel parts. The PMMA is removed, and the nickel parts may remain anchored to the substrate or be released.

UV LIGA



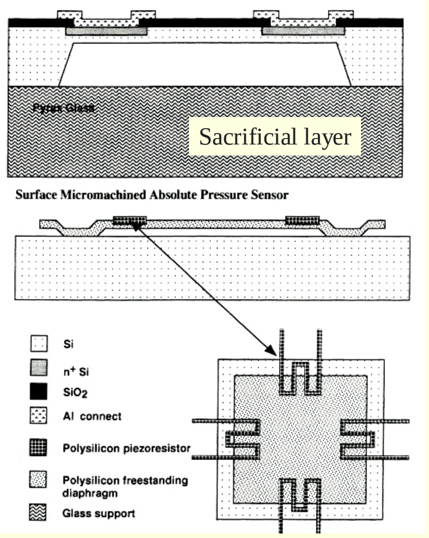
SU8

http://www.cee.hw.ac.uk/microengineering/microsystems/uv-liga/

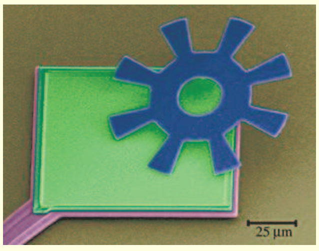
MEMS Devices By LIGA Process

Surface Micromachining

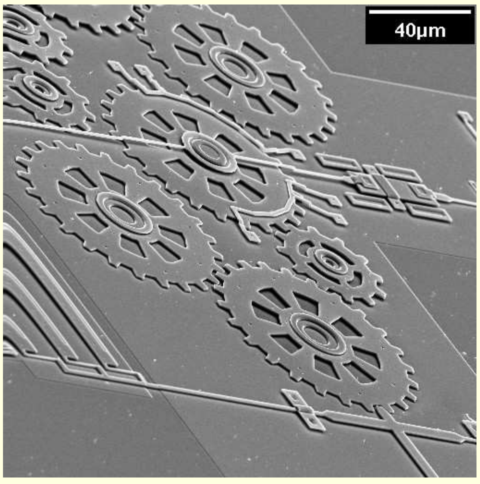
- Low hight ~2 µm (thickness of the film)
- Simple, flexible, variety of materials and deposition/etching techniques. But dimensions and materials are limited by selectivity of etching
- Compatible with IC
- Polycrystalline materials -> worse mecahnical and electrical characteristics (N.B. Whether it is worse depends on application)



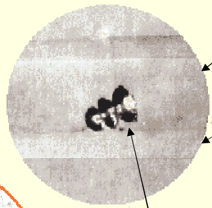
MEMS With Surface Micromachining

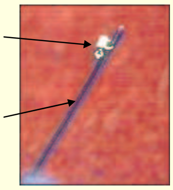


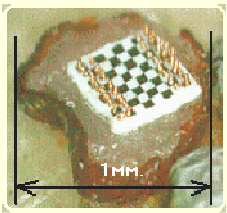
A colorized SEM picture of mechanical gear which is smaller than a human hair. The gear was made from polycrystalline silicon using *surface micromachining techniques* and is no longer attached to the substrate.
http://www.mems-exchange.org/gallery/



Manual Micromachining by Russian Craftsmen





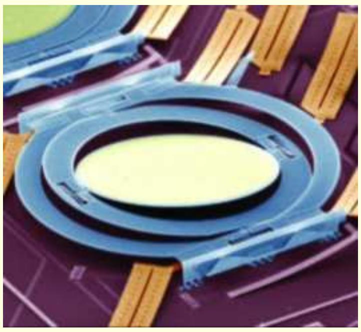


Alexander Perevoshchikov from Udmurtia; Izevsk: well known armourers’ town; central Russia

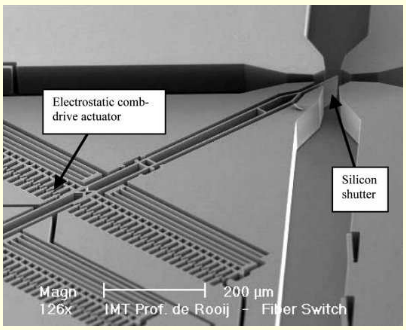
Pavel Kulikov, a MEMS locksmith lives and works in the town of Pavlovo, near Nizhni Novgorod in central Russia

BBC News: 11 April, 2001, UK

MEMS in Optics



Two axis beam steering micro-mirror built using surface micro-machined technology [8], (Lucent Technologies Inc./Bell Labs).



Piezoresistivity in Si

$$\frac{\Delta R}{R} = \sigma_l \pi_l + \sigma_t \pi_t$$

σ – stress component (logitudinal or transversal with respect to direction of current)
π – piezoresistance coefficient

	ρ (Ω cm)	π_{11}	π_{12}	π_{44}
p-Si	7.8	6.6	-1.1	138.1
n-Si	11.7	-102.2	53.4	-13.6

10^{-12} cm^2 dyne^{-1} or 10^{-11} Pa^{-1}

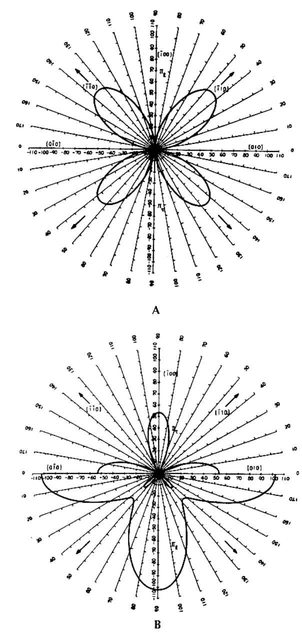


FIGURE 4.17 Piezoresistance coefficients π_l and π_t for (100) silicon. (A) For p-type in the (001) plane (10^{-12} cm^2/dyne). (B) For n-type in the (001) plane (10^{-12} cm^{-2}/dyne). (From Kanda, Y., *IEEE Trans. Electr. Dev.*, ED-29, 64–70, 1982. With permission.)

Piezoresistance Sensors

Place your resistors this way:

σ_l =10 MPa, σ_t=50 MPa:
ΔR/R = 3%

Up to about 10 mV/kPa sensitivity of a final pressure sensor

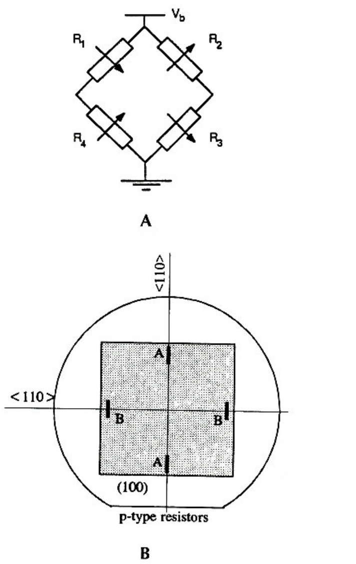
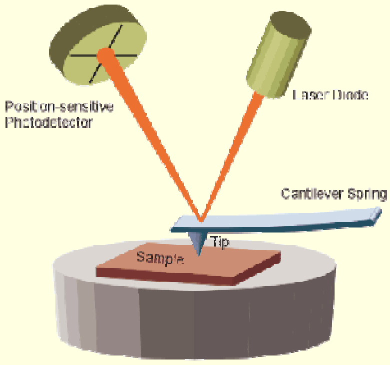
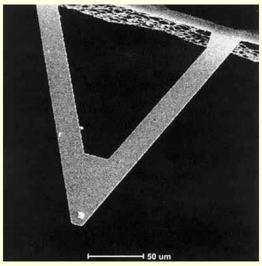
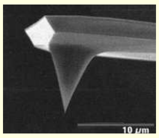


FIGURE 4.18 Measuring on a membrane with piezoresistors. (A) Wheatstone-bridge configuration of four in-diffused piezoresistors. The arrows indicate resistance changes when the membrane is bent downward. (B) Maximizing the piezoresistive effect with p-type resistors. The A resistors are stressed longitudinally and the B resistors are stressed transversally. (From Peeters, E., Ph.D. Thesis, KUL, Belgium, 1994. With permission.)

Cantilevers







Wet Etching

Isotropic

- Removal of work-damaged surfaces
- Rounding of sharp corners to avoid stress concentrations
- Removal of roughness after the anisotropic etching
- Thinning
- Patterning of thin films

Anisotropic

- High aspect ratios structures
- Excelent mechanical properties because of single-crystalline materials used

- Hard to control dimensions (but stop layers)
- Not very compatible with IC

Isotropic Wet Etching

Etch rate

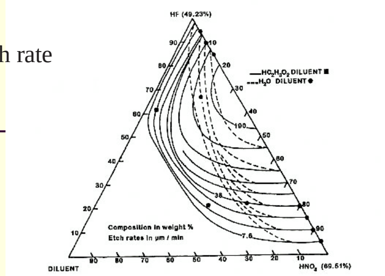
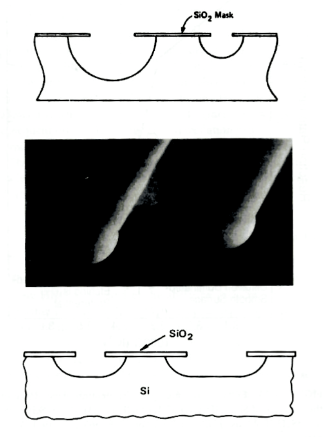


FIGURE 4.21 Iso-etch curves. From Robbins et al.,[5] recalculated for one-sided Si etching and expressed in µm/min.



Isotropic etching of Si with (A) and without (B) etchant solution agitation.

Morphology

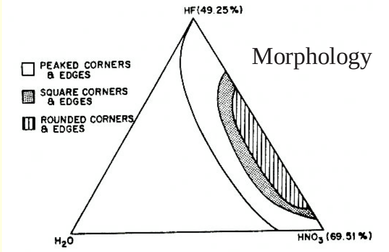
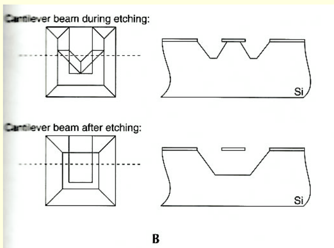


FIGURE 4.22 Topology of etched Si surfaces. (From Schwartz, B. and H. Robbins, *J. Electrochem. Soc.*, 123, 1903–1909, 1976. With permission.)

Anisotropic Wet Etching



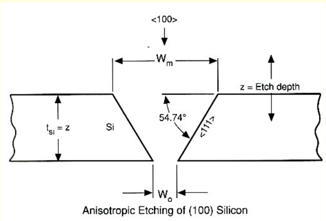
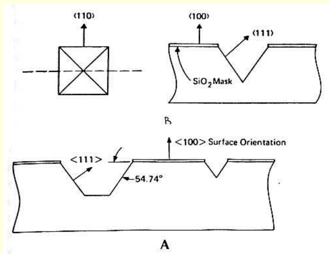


FIGURE 4.8 Relation of bottom cavity plane width with mask opening width.



Chemicals

Isotropic
$HF:HNO_3:CH_3COOH:H_20$
HF
$HF:NH_4F$

Masking Materials
Photoresist (Acids Only)
Si_3N_4
SiO_2

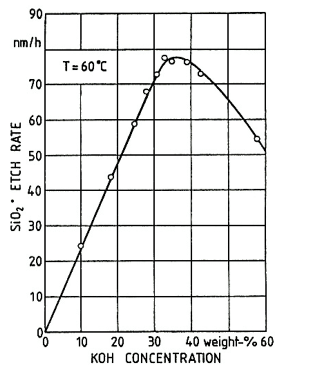
Anisotropic
KOH
EDP (Ethylenediamine Pyrocatechol)
CsOH
NaOH
N_2H_4-H_20 (Hydrazine)

Chemicals

KOH Etching
Etch rate

(110) > (100) > (111)
(111) > (110) > (111) w/ IPA

Varies with *T* and concentration

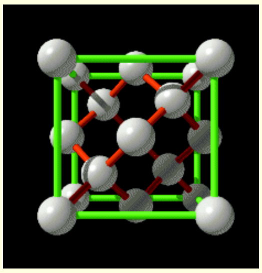


The SiO_2 etch rate in nm/hr as a function of KOH concentration at 60°C. (From Seidel, H. et al., *J. Electrochem. Soc.*, 137, 3612–3626, 1990. With permission.)

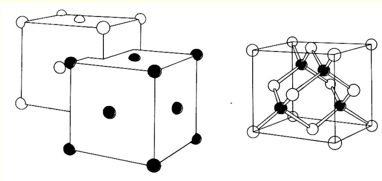
Masks
Si_3N_4: is the best, very slow etch rate, selectivity > 1000
SiO_2 :selectivity >> 100

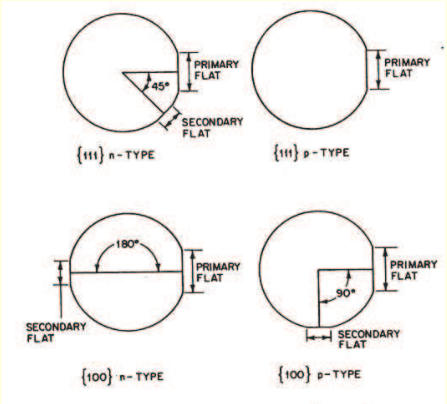
Si Crystal Structure

diamond structure



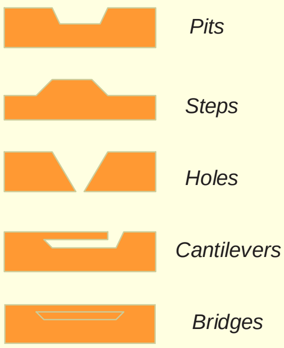
Two interleaving FCC cells offset by 1/4 of the cube diagonal





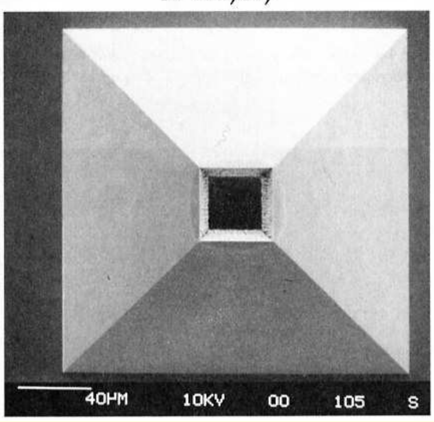
Primary and secondary flats on silicon wafers.

Application of Anisotropic Etch



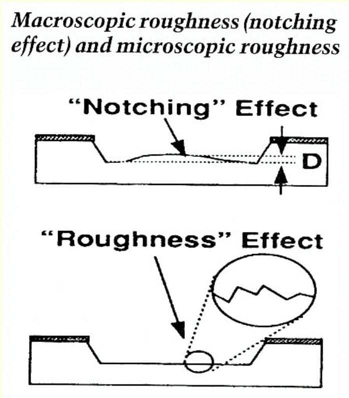
Micromachining

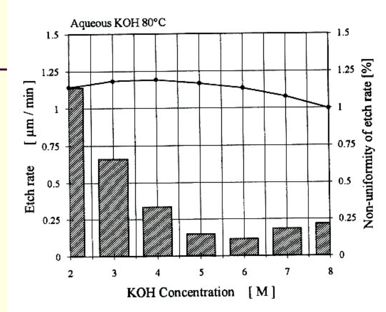
Orifice (A via through Si wafer)

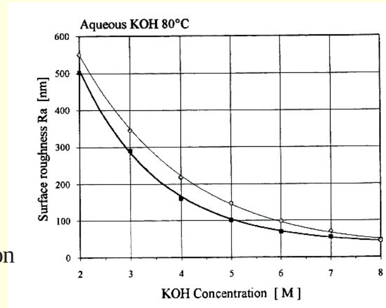


M. Madou "Fundamentals of microfabrication"

Anisotropic Wet Etching: Problems



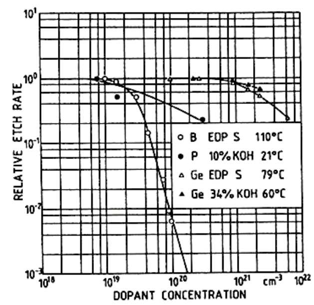




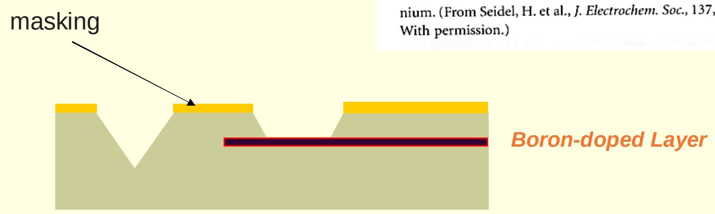
Depends on KOH concentration

Etch Stop Layers

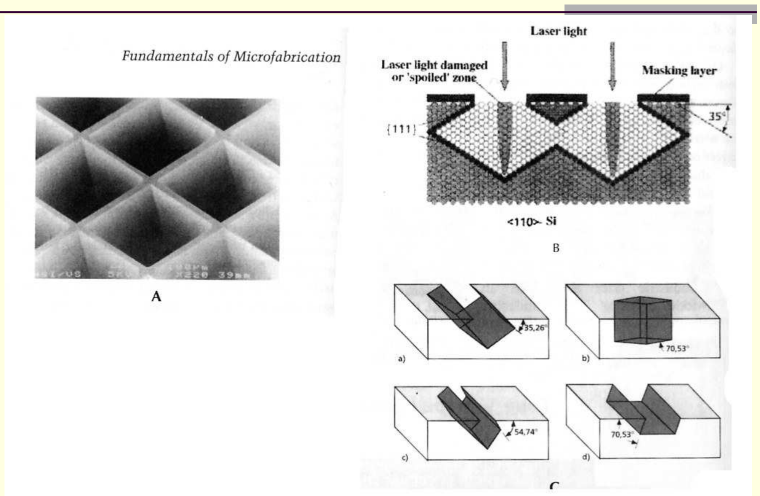
Boron Stops Etching
~10^{20} cm^{-3} reduces etch rate 1000 times



Relative etch rate for (100) Si in EDP and KOH solutions as a function of concentration of boron, phosphorus, and germanium. (From Seidel, H. et al., *J. Electrochem. Soc.*, 137, 3626–3632, 1990. With permission.)



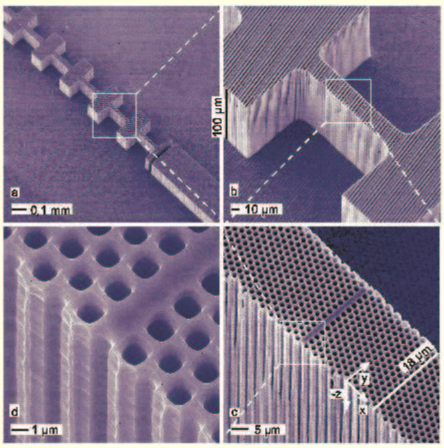
Laser-Assisted Wet Etching

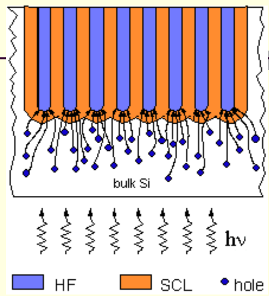


M. Madou, Fundamentals of Microfabrication

Macroporous Si

http://www.macroporous-silicon.com/

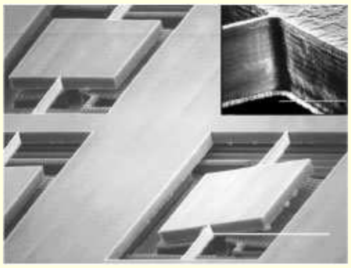




Photogenerated minority carriers (in the case of n-type Si this means "holes") diffuse from the back side of the sample to the pore (etch) pits and promote dissolution there, because of the enhanced electrical field in the space charge layer (SCL).

www-tkm.physik.uni-karlsruhe.de/

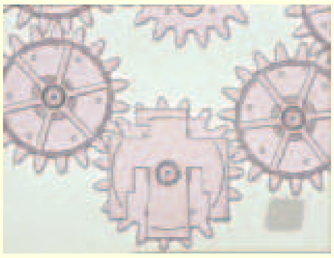
Assorted Gallery of MEMS Devices



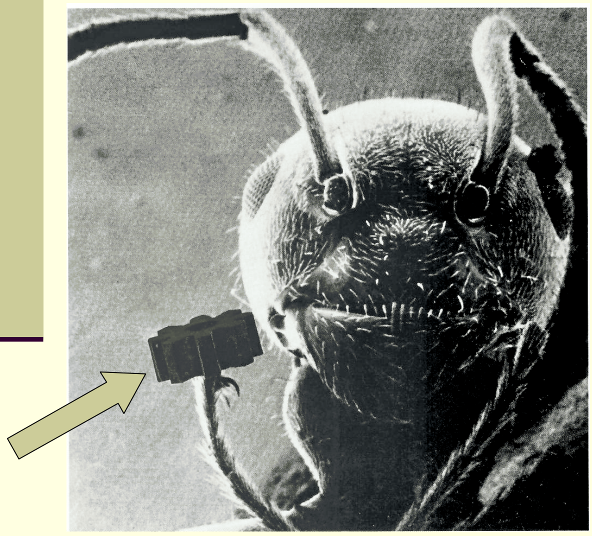
Made of Ti

Made of Si / M

Assorted Gallery of MEMS Devices



Assorted Gallery of MEMS Devices



Thanks for listening!

M. Madou "Fundamentals of microfabrication"