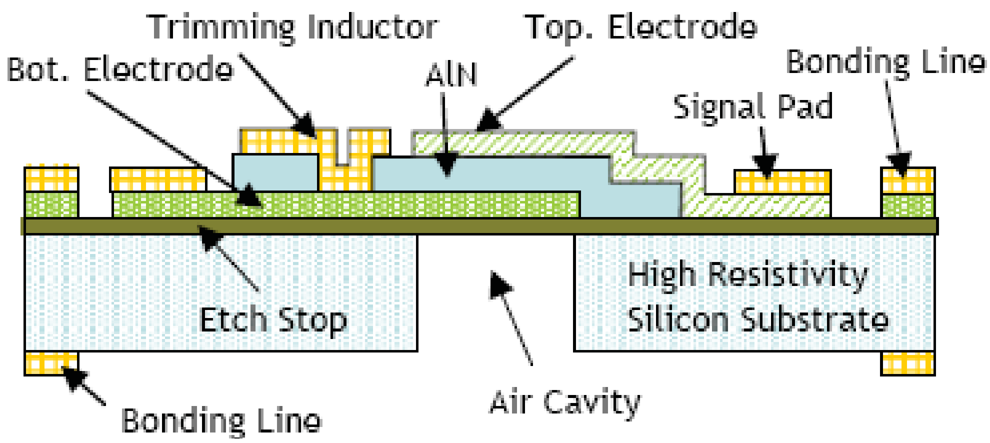
Microsystems technology S-129.3210 (5ECTS)

Exam January 9, 2006, hall S5, 9-12 o'clock   Tittonen/Franssila

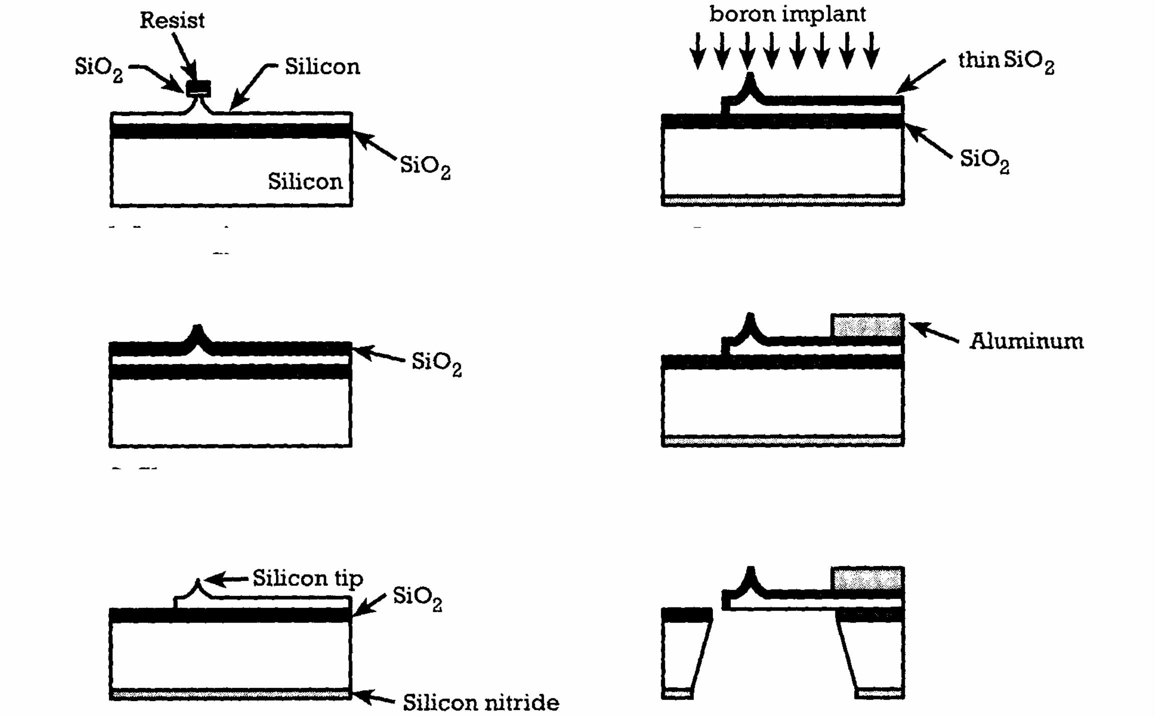
Answer 4 out of 6 questions (==> 24 points). Exercises 18 points max. 36 p. total.

1. Explain step-by-step the fabrication steps of the resonator plate shown below. Also discuss materials properties and estimate linewidths and film thicknesses.
(Hint : Bonding line, trimming inductor and signal pad are aluminum.)



Ha et al, Transducers ´05, p. 2069

2. A process to fabricate AFM needles is shown below. Explain the fabrication steps with special attention to etching steps. (Your answer must also cover those steps that have been made even though no picture is explicitly referring to those steps.)



3. MEMS-materials

a) Compare given materials generally for MEMS-applications in terms of cost and processability. Give examples of fabrication methods available to process and/or grow given materials. Also comment on using (two or more of the mentioned) materials in the fabrication of the same device (etching selectivity, thermal expansions etc…).

b) Compare material parameters concerning the suitability (pros and cons when compared to other materials: Mechanical and electrical properties, Actuation (and possibly read-out), Fabricational aspects etc…) of the material for a device when the device to be fabricated is i) High-frequency resonator ii) (Contact-Shunt-) Switch.

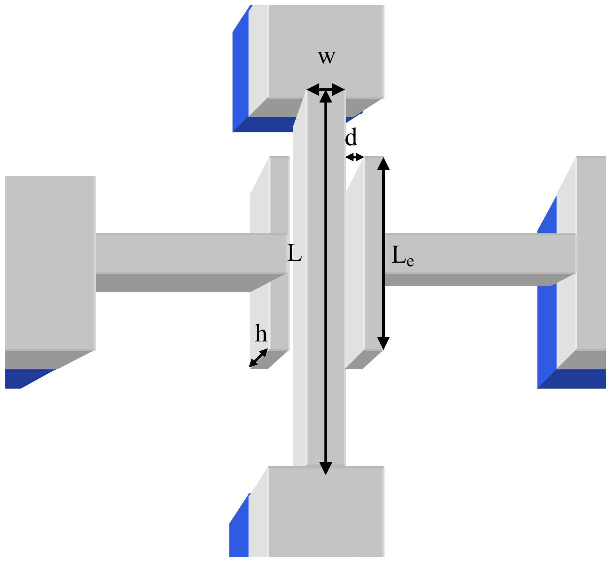
The materials are:
I) Silicon (Si)
II) Quartz (SiO_2)
III) Diamond (Di)
IV) Aluminium (Al)

4. a) For a beam resonator presented below calculate the force *F* affecting the beam on frequencies 0 (static), ω, 2·ω when

i) Voltage $u = u_{ac}*sin(\omega t)$ is applied on the left hand side electrode and the resonator is grounded.
ii) Voltages $u = u_{ac}*sin(\omega t)$ and $U = U_{DC}$ are both applied on the left hand side electrode and the resonator is grounded. (2 p.)

(Hint: Assume that the displacement *x* is small when compared to the initial coupling gap *d*)

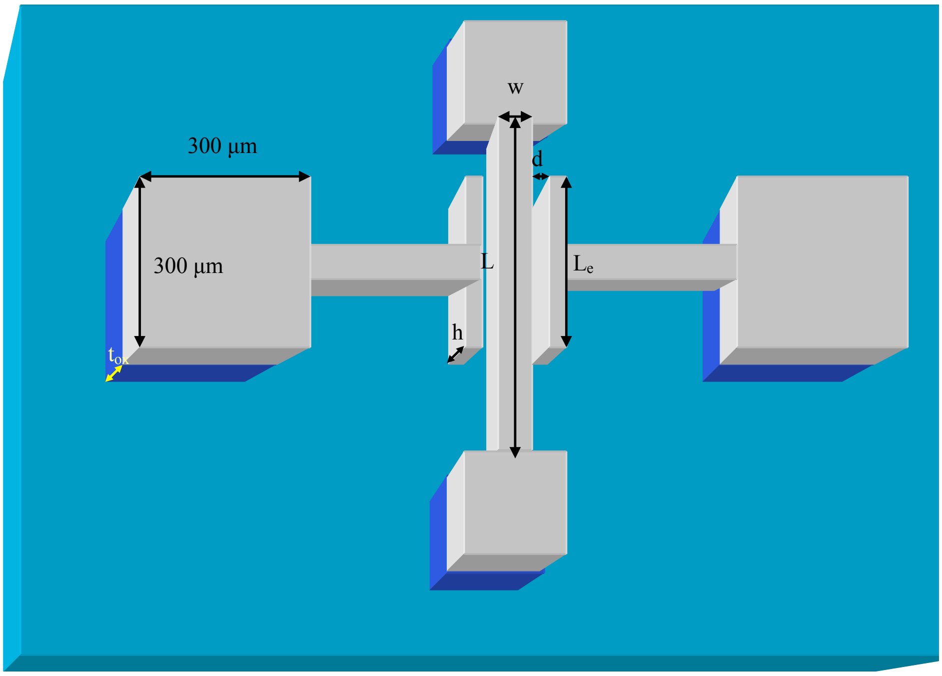
L	100 µm
L_e	75 µm
w	5 µm
d	1 µm
h	10 µm
u_{ac}	500 mV
U_{DC}	100 V



b) Calculate the motional current on the right hand side electrode in the case ii) above when *ω* is the fundamental resonance frequency of the beam. (2 p.)
(Hint: Assume that the displacement *x* is small when compared to the initial coupling gap *d*)

c) Outline the process steps needed to fabricate this resonator on a device (top) layer of a SOI-wafer. (2 p.)

5. a) Sketch an equivalent circuit representation of a resonator below. Remember to add the feed-through capacitance and pad capacitances Note that the picture is not to scale. (1 p.)



L	100 µm
L_e	75 µm
w	5 µm
d	1 µm
h	10 µm
t_{ox}	2 µm

Key:	
	Device silicon
	Silicon dioxide
	Structural silicon

b) Calculate the component values for the equivalent circuit. Remember that you will need to use effective value for the mass (m_{eff}) instead of the dimensional value. Estimate the order of magnitude of feed-through and pad capacitaces and back them up by order-of-magnitude calculations. The resonator is fabricated on a SOI-wafer. Assume the quality factor of the resonator to be Q = 2000 and both electrodes to be biased with a voltage U_{DC} = 100 V. (2 p.)

c) Impedance matching is (always) important and the problem with many MEMS-devices is that they have very large mechanical impedance (hard to match for 50 Ω). Suggest feasible methods to **lower the mechanical impedance of the resonator** while keeping the resonance frequency (almost) constant. Give some estimate values for the changed parameters and their effect for the fabrication of the structure and modified R_m. (1 p.)

d) In an international MEMS-conference Dr. Strangelove presents a new plate-resonator. He tells that the quality factors reached are in the order of Q = 200 000. By that he argues that the impedance levels of this resonator are smaller by a factor of 100 when compared to the resonator presented above (Q = 2000) and therefore R_m = 50 Ω could be reached. Study the data presented in the"poster" on the following page and comment his claims. Back-up your comments by calculations. Assume that the measured data and given equations are correct. (2 p.)

Reducing the mechanical impedance by plate-resonator

We present a novel plate-resonator. Quality factor of the resonance is measured to be around $Q = 200\,000$. This two orders of magnitude improvement in the quality factor when compared with the conventional resonator leads to 100 times smaller motional resistance (Eq. 1)

The mechanical resistance of a micromechanical resonator can be written as

$$R_m = \frac{\sqrt{k \cdot m}}{Q\eta^2} \qquad \text{(Eq. 1)}$$

The resonator is fabricated on a Silicon-on-insulator (SOI) –wafer with the following dimensions

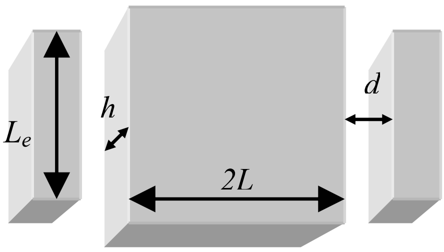


Fig. 1. *Plate-resonator with excitation and readout electrodes. Both electrodes are biased with a voltage U_{DC} and the resonator is grounded. Numerical values for dimensions are in Table 1.*

The fundamental resonance frequency of the resonator can be calculated from the equation below

$$f_r = \frac{1}{4L}\sqrt{\frac{E}{\rho}} \qquad \text{(Eq. 2)}$$

Results for the displacement of the edge x when a force F is applied at the edge of the structure (Fig 2.) are presented in Table 2.

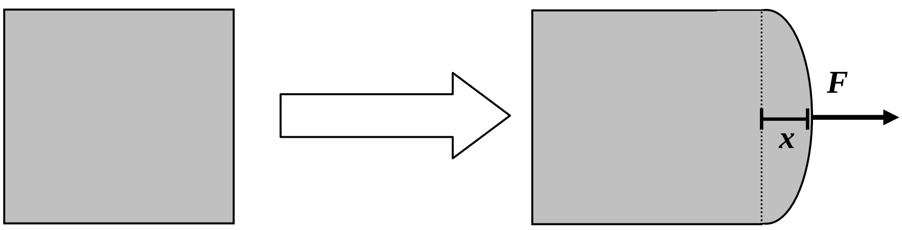


Fig. 2. *A mechanical force F was applied at one edge of the resonator and the displacement x was recorded. The results are shown in Table 2.*

Table 1. Dimensions

L	*160 µm*
Le	*75 µm*
h	*10 µm*
d	*1 µm*
U_{DC}	*100 V*

Table 2. Force-displacement measurements

***F* [N]**	***x* [nm]**
0.1	*77*
0.3	*231*
0.8	*615*
1	*770*

6. Explain step-by-step the fabrication process of the microvalve shown below. Estimate dimensions, identify materials and describe processes used. Remember to keep track what is taking place on wafer backside when top side is being processed and vice versa

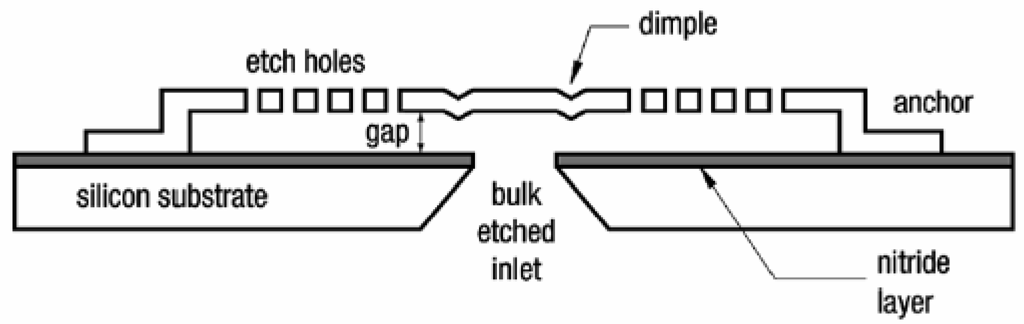


Fig. 1. Microvalve cross section. Note that the gap height dimension is exaggerated for clarity.

From: J. Collier et al, J.MEMS 13 (2004), 912

Equations and constants

Clamped-free beam (beam clamped at the one end while the other is free)

1^{st} resonance frequency: $$f_1 = 0{,}162\sqrt{\frac{E}{\rho}}\left(\frac{w}{L^2}\right)$$

spring constant: $$k = \frac{Eh}{4}\left(\frac{w}{L}\right)^3$$

Clamped-clamped beam (both ends clamped)

1^{st} resonance frequency: $$f_1 = 1{,}03\sqrt{\frac{E}{\rho}}\left(\frac{w}{L^2}\right)$$

spring constant: $$k = 16Eh\left(\frac{w}{L}\right)^3$$

Equivalent circuit values:

$$R_m = \frac{\sqrt{km_{eff}}}{Q\eta^2},$$

$$L_m = \frac{m_{eff}}{\eta^2},$$

$$C_m = \frac{\eta^2}{k}.$$

Current generated by moving beam in biased coupling gap: $i = U\frac{\partial C}{\partial x}\dot{x}$

Resonance frequency of a mass-spring-system: $$\omega_0 = \sqrt{\frac{k}{m}}$$

Coupling coefficient: $$\eta = U\frac{\partial C}{\partial x}.$$

Pull-in voltage: $$U_{pi} = \sqrt{\frac{8\cdot kd^2}{27\cdot C_0}}$$

Dielectric-constant of vacuum	$\varepsilon_0 = 8.85\cdot10^{-12}$ F/m
Relative dielectric-constant of silicon	$\varepsilon_{Si} = 11.9$
Relative dielectric-constant of silicon-dioxide	$\varepsilon_{SiO2} = 3.9$
Relative dielectric-constant of diamond	$\varepsilon_{Di} = 5.7$
Young's modulus of silicon	$E_{Si(100)} = 130$ GPa
Young's modulus of quartz	$E_{SiO2} = 73$ GPa
Young's modulus of diamond	$E_{Di} = 1035$ GPa
Young's modulus of aluminium	$E_{Al} = 70$ GPa
Density of silicon	$\rho_{Si} = 2330$ kg/m^3
Density of quartz	$\rho_{SiO2} = 2650$ kg/m^3
Density of diamond	$\rho_{Di} = 3500$ kg/m^3
Density of aluminium	$\rho_{Al} = 2700$ kg/m^3