Version AAS/4

EGT3
ENGINEERING TRIPOS PART IIB

Thursday 3 May 2019 9.30 to 11.10

Module 4C15

MEMS DESIGN

Answer not more than ***three*** *questions.*

All questions carry the same number of marks.

The ***approximate*** *percentage of marks allocated to each part of a question is indicated in the right margin.*

Write your candidate number ***not*** *your name on the cover sheet.*

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Attachment: 4C15 MEMS Design data sheet (4 pages).
Engineering Data Book

10 minutes reading time is allowed for this paper at the start of the exam.

You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.

1 A MEMS cantilever (Fig. 1) used for atomic force microscopy consists of a spherical tip of radius R = 100 nm and spring constant k = 10 N m^{-1}. The cantilever tip is brought into close proximity of a flat substrate by bending the cantilever such that h is the gap spacing between the tip of the cantilever and the substrate as shown. The work of adhesion of the surfaces w is 1 J m^{-2} and the equilibrium gap spacing h_0 is 0.2 nm.

(a) The net van der Waals force of attraction $F(h)$ between a spherical surface of radius R and a planar surface can be written as

$$F(h) = \frac{8\pi R w}{3}\left\{\left(\frac{h}{h_0}\right)^{-2} - \frac{1}{4}\left(\frac{h}{h_0}\right)^{-8}\right\}$$

Sketch the form of this relationship highlighting salient features and obtain a value for h in terms of h_0 for $F(h) = 0$. [30%]

(b) Obtain an estimate for the gap spacing h when the cantilever snaps into the substrate. [30%]

(c) Derive an expression for the maximum force between the tip and the substrate. [20%]

(d) Estimate the reduction in the magnitude of the pull-off force for this cantilever if the work of adhesion is reduced to 10 mJ m^{-2} through surface treatment. [20%]

Fig. 1

2 A micromachined electromechanical device consists of a spring-supported electrically grounded beam sandwiched between two gap closing electrodes as shown in Fig. 2. The nominal gap spacing between each fixed electrode and the beam is g with no voltage applied and the electrode overlap area is A. The net effective mechanical spring constant of the beam is k. It is assumed that the surfaces remain parallel during operation and there is no adhesion between the beam and electrode surface when the beam has pulled in.

(a) The beam is initially centred between the electrodes as shown. Switch S1 is then closed with switch S2 held open such that both electrodes are electrically shorted and biased at voltage V_1 with respect to the beam.

(i) Obtain an expression for the net electrostatic force acting on the beam. [20%]

(ii) Obtain expressions for the pull-in displacement and pull-in voltage for the beam. [50%]

(iii) After the beam has pulled into electrode 1, voltage V_1 is reduced to 0 V. Discuss the subsequent response of the beam assuming that the device is packaged under atmospheric pressure. [10%]

(b) The beam is subsequently returned to the initial condition outlined in (a) again but with the switch S2 now closed and the switch S1 held open. Voltage V_1 is still 0 V while voltage V_2 is varied until pull-in. Obtain an estimate for the pull-in voltage V_2 and compare this to your expression in (b). [20%]

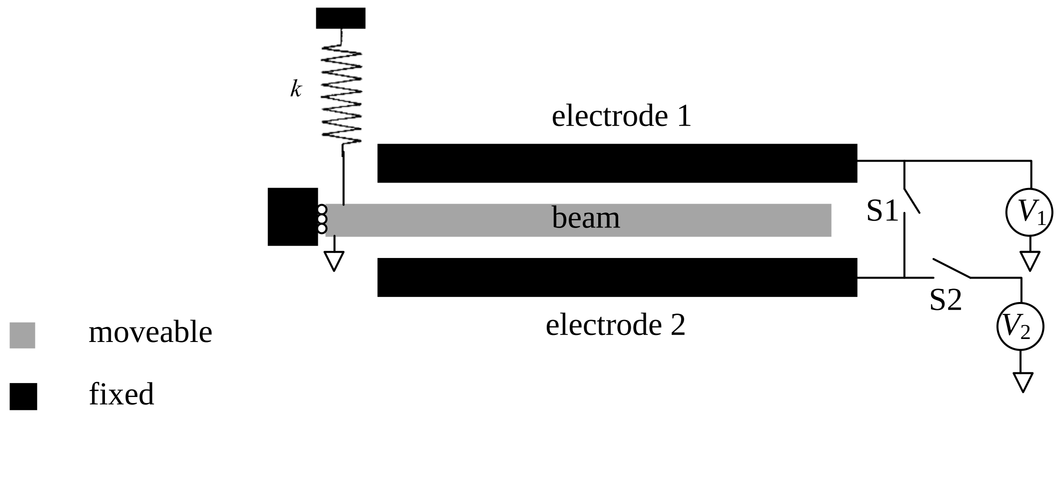

Fig. 2

3 A z-axis silicon micromachined vibrating rate gyroscope is shown in Fig. 3. The device consists of a 100 μm thick suspended mass in the form of a square plate with side dimension 5 mm. The mass is designed to be compliant along the two in-plane directions with a drive mode natural frequency of 2 kHz and a sense mode natural frequency of 2.1 kHz. The proof mass is actuated in the drive mode using comb drive electrodes comprising N = 500 electrode gaps with a gap spacing of 1 μm and an overlap length of 10 μm. The gap between the suspended mass and the fixed substrate is 2 μm and the mass of the comb fingers may be neglected. The device is packaged in an inert atmosphere and the operating temperature is T = 300 K. The dynamic viscosity of the fluid surrounding the micromechanical device is 1.8×10^{-5} kg m^{-1} s^{-1} and the relative permittivity of the fluid is 1.

(a) Estimate the Quality factor for resonant motion in the drive direction assuming that the damping in this direction is limited by Couette drag. [20%]

(b) Estimate the displacement in the drive mode if the gyroscope is actuated by a sinusoidal AC voltage of 100 mV and a DC voltage of 10 V with the primary forcing component resulting in resonant actuation in the drive direction. [20%]

(c) Estimate the Quality factor for motion in the sense mode assuming that squeeze film damping between the comb fingers is also operative. [20%]

(d) Estimate the sense displacement if a rotation rate of 1 deg sec^{-1} is applied about the z-axis. [20%]

(e) Estimate the thermo-mechanical noise limited resolution of the device. [20%]

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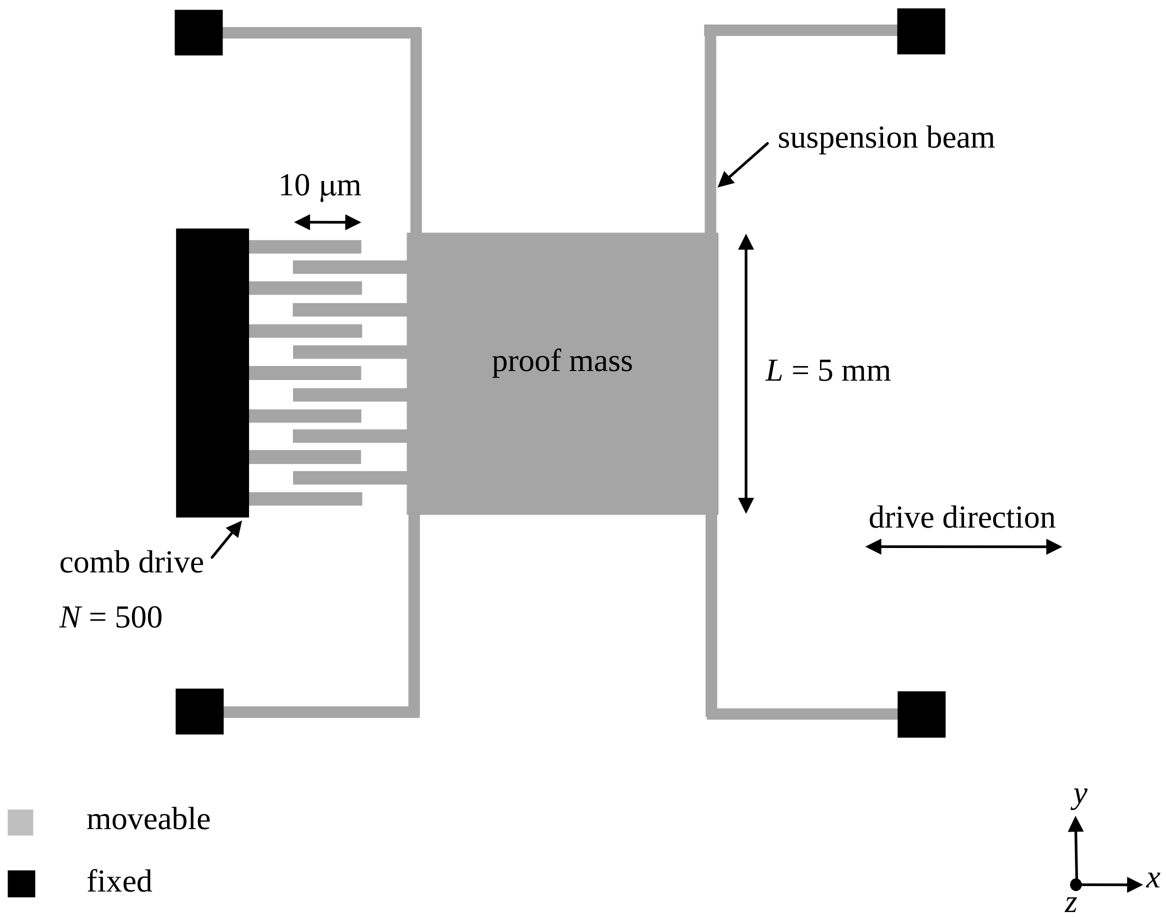
suspension beam
10 μm
proof mass
L = 5 mm
drive direction
comb drive
N = 500
moveable
fixed
y
x
z

Fig. 3

4 A vacuum-packaged clamped-clamped beam resonator with a resonance frequency of 400 kHz and a Quality factor Q of 50000 is implemented in a polysilicon surface micromachining process as shown in Fig. 4. The structural thickness of the device layer is 25 μm and the effective mass m is equal to 0.139 μg. Two parallel plate electrodes are provided for actuation and sensing respectively as shown. The nominal overlap length L of the electrodes is 200 μm and the gap spacing g between each pair of fixed and moveable electrodes is 2 μm. The resonator is driven using a combination of a sinusoidal AC voltage v_{ac} with a frequency of 400 kHz and a DC bias voltage V_P applied to the drive electrode with respect to the beam resonator. The motion is transduced by measuring the capacitive current generated due to the motion of the beam at the sensing electrode which is also biased at a voltage V_P with respect to the beam.

(a) Estimate the magnitude of the electrostatic force at 400 kHz if v_{ac} = 200 mV and V_P = 10 V. [20%]

(b) Estimate the amplitude of the motional current at resonance for the conditions outlined in (a). [20%]

(c) Derive expressions for the electromechanical motional parameters of this device and calculate specific values of these parameters for the drive conditions outlined in (a). [20%]

(d) Sketch graphs showing the dependence of the motional resistance as a function of the bias voltage, transduction gap, and structural thickness. Hence, discuss approaches to minimise motional resistance subject to manufacturing constraints [20%]

(e) List three possible sources of nonlinear behaviour in this resonator. [20%]

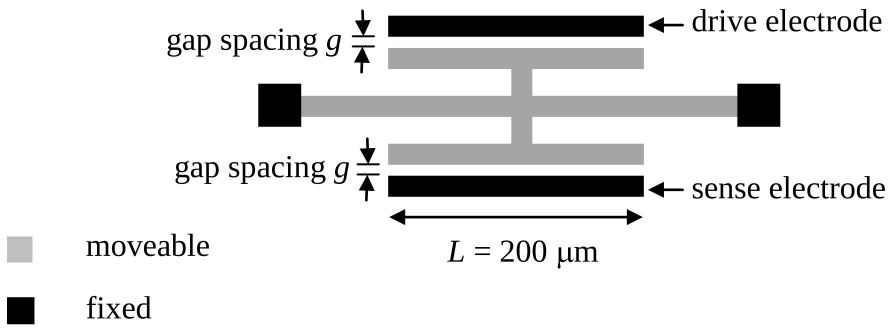

Fig. 4

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