ENGINEERING TRIPOS PART IIB

ELECTRICAL AND INFORMATION SCIENCES TRIPOS PART II

Saturday 3 May 2003 9 to 10.30

Module 4C13

MEMS

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.*

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

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The following formulae can be quoted without proof:

Hertzian point contact under load P

Reduced radius R given by $\dfrac{1}{R} = \dfrac{1}{R_1} + \dfrac{1}{R_2}$

Contact modulus E^* by $\dfrac{1}{E^*} = \dfrac{1-\nu_1^2}{E_1} + \dfrac{1-\nu_2^2}{E_2}$

Radius of contact circle $a = \left\{\dfrac{3PR}{4E^*}\right\}^{1/3}$

Contact pressure $p = p_0\left\{1 - r^2/a^2\right\}^{1/2}$

Maximum contact pressure $p_0 = \dfrac{3P}{2\pi a^2} = \left\{\dfrac{6PE^{*2}}{\pi^3 R^2}\right\}^{1/3}$

Mean contact pressure $\bar{p} = \dfrac{2}{3} p_0$

Approach of distant points $\delta = \dfrac{a^2}{R} = \left\{\dfrac{9P^2}{16RE^{*2}}\right\}^{1/3}$

Maximum shear stress is of magnitude $0.31 p_0$ at $r = 0$ and depth $0.48a$.

Elastic contact with adhesion, JKR: $\dfrac{4E^* a^3}{3R} = P + 2\sqrt{2\pi w E^* a^3}$

Archard wear: dimensional wear rate $\propto \dfrac{\text{pressure} \times \text{sliding speed}}{\text{hardness}}$

Elastic flexure of a thin cantilever: tip deflection $= \dfrac{WL^3}{3EI}$; tip rotation $= \dfrac{WL^2}{2EI}$

1 (a) Describe what is meant by:

(i) bulk micromachining;

(ii) surface micromachining,

with particular reference to silicon micro-electro-mechanical systems (MEMS). Sketch cross-section diagrams in your answer to explain the fabrication processes involved in each case. [40%]

(b) Using the example of acceleration sensors, discuss the relative merits of surface and bulk micromachined devices with respect to device sensitivity, manufacturing cost and sensor reliablility. Illustrate your answer with brief accounts of successful products. [30%]

(c) Describe briefly why surface properties and surface phenomena have more significance in MEMS than in typical macro-scale systems. What is stiction and how are the possible effects of stiction reduced during the manufacture of MEMS accelerometers? [30%]

2. (a) Explain briefly why the phenomenon of adhesion between dry surfaces is of more relevance in the operation of MEMS devices than in conventional macroscopic devices. [20%]

(b) If two smooth but dissimilar surfaces are brought into close proximity so that they are at a separation distance h then the pressure between them $p(h)$ can be written as

$$p(h) = \frac{8w}{3h_0}\left\{\left(\frac{h}{h_0}\right)^{-3} - \left(\frac{h}{h_0}\right)^{-9}\right\}$$

where w is the 'pull-off' work. What is the significance of the separation h_0? What is the relation of w to the surface energies of the two materials concerned? [20%]

(c) Show that if such an adhesive junction is subjected to an externally applied tensile stress, then 'pull-off' will occur when the separation has reached a magnitude of $3^{1/6}h_0$. Hence, obtain an expression for σ_{th} the theoretical strength of the junction. [20%]

(d) Explain why an effective elastic modulus E of the contact can be defined by

$$E = h_0\left[\frac{\mathrm{d}p(h)}{\mathrm{d}h}\right]_{h=h_0},$$

and show that σ_{th} is approximately $0.06E$. [20%]

(e) In practice, levels of adhesion are almost always very much less than this; suggest why this might be so? [20%]

3 (a) Explain briefly why the behaviour of macroscopic devices is often dominated by considerations of inertia while at the micro-scale surface phenomena are generally of more importance. [15%]

(b) The rotor of a MEMS motor can be thought of as a silicon disc located by a central hub as shown in Fig. 1. The axial thrust load P on the rotor is carried by three equally spaced ribs which are of width c and extend from radius a to radius b. These ribs bear against the lower substrate which is made of silicon carbide.

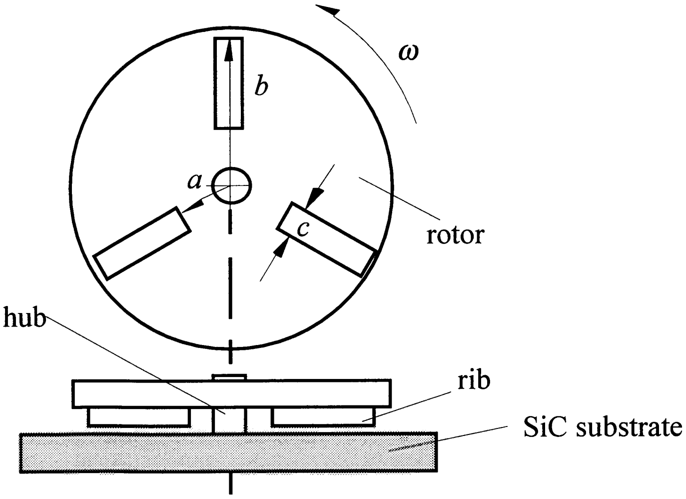

Fig. 1

If it is the three supporting ribs that wear and this phenomenon can be described by the Archard wear law, obtain an expression for the way in which the interfacial pressure due to the axial load P is distributed along each of the ribs. [25%]

(c) If the Archard wear constant for Si against SiC is 2×10^{-7} mm^3 N^{-1} m^{-1} what volume of debris will be produced after one hour of continuous running at 25,000 rpm if $P = 5$ mN, $b = 100$ μm, $a = 30$ μm and $c = 20$ μm? [25%]

(d) If the coefficient of friction between Si and SiC under these circumstances is 0.16 what is the frictional torque developed in the motor? [25%]

(e) How might the tribological performance of the motor be improved? [10%]

4 (a) Describe briefly the main methods used to:

(i) grow or deposit films for MEMS devices on silicon substrates;

(ii) remove or etch structures.

In each case, indicate which methods are actually used in manufacturing and which are primarily used for research and the development of prototype MEMS. [40%]

(b) Figure 2 is the plan view of a SiC coated perfectly oriented (100) silicon wafer in which the black pattern has been etched through the SiC layer. The small grid points are 10 μm apart. The silicon is then etched to termination using an anisotropic etchant which is perfectly selective against SiC, and which has zero etch for (111) type crystal planes in the silicon.

(i) For the case in which the SiC etch pattern is oriented on the surface of the Si to give the *minimum* final etch depth, calculate the etch depth in μm into the silicon after etching to termination.

(ii) Sketch a cross section through the SiC/Si structure for case (i) along the line MN in Fig. 2.

(iii) For the situation in which the pattern is oriented to give the *maximum* etch depth into the Si, determine the final etch depth in μm.

(iv) Consider case (iii) and an etch rate of 0.5 μm per minute. If the (111) planes etch at 10% of this rate, make an approximate calculation and hence plot the depth of the deepest part of the structure as a function of time. State any assumptions you make. [60%]

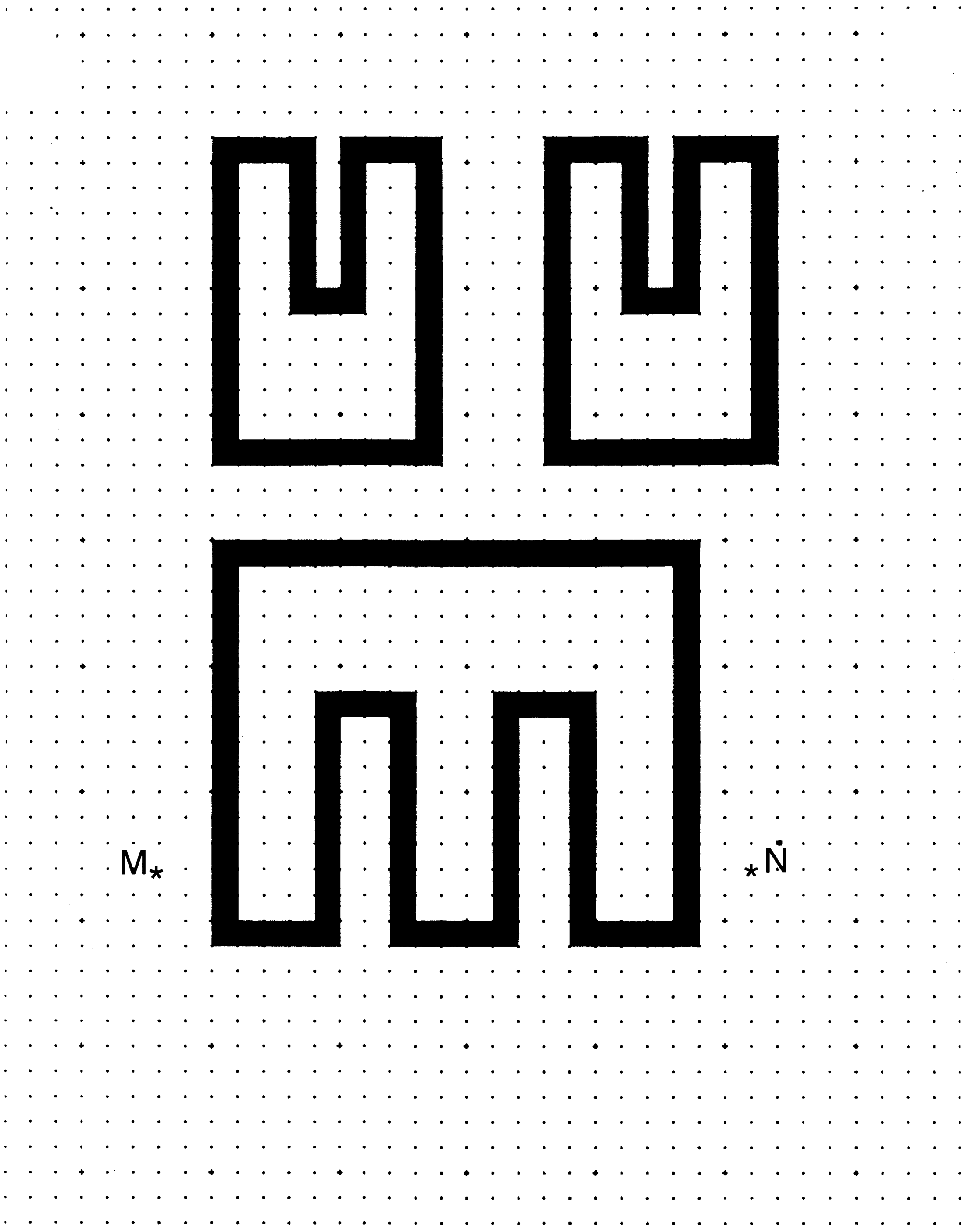

Fig. 2

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5 (a) Explain why micromechanical beams are often used in silicon MEMS, giving brief accounts of two applications. Outline a possible process to fabricate silicon nitride beams starting with a bare silicon substrate. [40%]

(b) Figure 3 shows data from a surface profilometer (Dektak) running along a silicon carbide beam 100 μm wide and 5 μm thick. The *x*-axis is the horizontal distance in the plane of the substrate (μm) with the origin at an arbitrary point, and the *y*-axis is the distance normal to the plane of the substrate (μm) with the origin on the plane of the substrate. The constant normal load on the stylus of the instrument is 400 μN.

(i) Explain how the data in Fig. 3 are taken and analyse the data to determine the extent to which the beam is behaving as a thin cantilever within the small deflection limit.

(ii) Estimate the Young's modulus of the silicon carbide, and comment on the possible errors in the measurement. [60%]

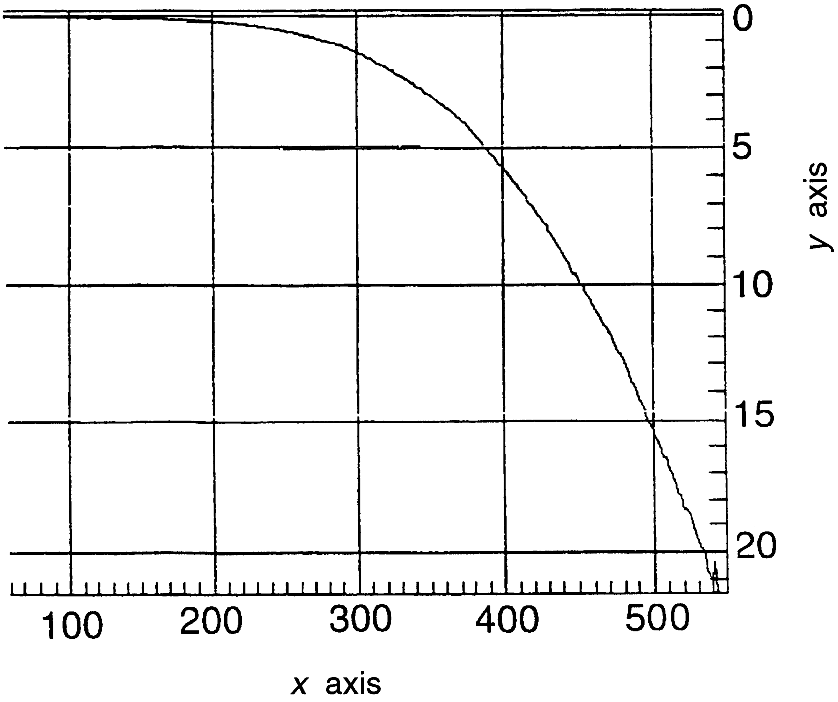

Fig. 3

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