2008 IIB 4M6 MATERIALS AND PROCESSING FOR MICROSYSTEMS (MEMS) DR AJ FLEWITT

ENGINEERING TRIPOS PART IIB

Friday 9 May 2008 2.30 to 4

Module 4M6 - ANSWERS

Version 2

1 (a) Materials selection in MEMS devices is affected by a number of factors. These will include the function of the device (its purpose, which might be to resonate at a particular frequency with minimum mass, or deflect under a particular load without fracture, for example). This will allow the generation of a figure of merit for comparing different materials. The geometry of the device will be important as not all materials can be produced in particular geometries. This is particularly true of microfabrication, where, for example, intrinsic stresses can limit the thickness of thin film materials. Finally, there is the process required to fabricate the device. Only certain materials can be produced by given techniques. In practice all of these factors are mixed together – photolithography might be required to pattern a given material, which limits the minimum feature size, for example. [25%]

(b) (i) The resonant frequency of a system is given by

$$\omega = \sqrt{\frac{k}{m}},$$

where m is the mass and k is the spring constant, which from the note to the question is given by

$$k = \frac{Ebh^3}{12l^3}$$

Also, the mass of the beam is related to the density ρ by $m = wlb\rho$, so therefore

$$\omega = \frac{h}{l^2}\sqrt{\frac{E}{12\rho}}.$$

Hence the figure of merit is that $\sqrt{E/\rho}$ should be maximised. [15%]

(ii) From the Young Modulus vs. density Ashby diagram in the Materials Data Book, it is clear that diamond would be suitable for this task, but it is difficult to make diamond in a thin film form that has a flat surface for good laser reflection. Therefore, diamond-like carbon should be chosen. Furthermore, DLC is biologically compatible and can be etched selectively against silicon. [15%]

(iii) A suitable process flow would be as follows:

Step	*Code*	*Description*	
1	RCA1	Boil the silicon substrate in RCA Clean 1 (NH3(aq):H2O:H2O2) to remove organic contaminants.	
2	RCA2	Boil the silicon substrate in RCA Clean 2 (HCl:H2O:H2O2) to remove metallic ion contaminants.	[5%]
3	SIN1	Deposit silicon nitride by LPCVD on the reverse side of the wafer to passivate.	[5%]
4	DLC1	Deposit the DLC thin film on the top side of the wafer by filtered cathodic vacuum arc.	[5%]
5	PHO1	Spin a layer of photoresist onto the top surface of the sample wafer. The photoresist should be thick compared with the thickness of the DLC.	
6	BAK1	Pre-bake the photoresist.	
7	EXP1	Expose the photoresist through a mask to produce a pattern in the photoresist that is a positive image of the cantilever structure, and aligned to the (110) planes in the silicon wafer.	
8	DEV1	Develop the photoresist.	
9	BAK2	Post-bake the photoresist to harden it.	[5%]
10	RIE1	Etch the DLC by reactive ion etching using an oxygen plasma.	[10%]
11	KOH1	Etch the sample in a 25% KOH solution at 80 °C to undercut the structure. The etch will naturally stop on the silicon nitride, which will also protect the structure from back-etching.	[5%]
12	DIW1	Rinse the sample in DI water and dry.	
13	RIE2	Etch the silicon nitride off the back side of the silicon wafer by reactive ion etching in a CF_4+O_2 plasma.	[5%]
14	RIE3	Expose the sample to a short O_2 rf-RIE plasma to remove any remaining polymer from the CF4 plasma etch.	[5%]

2 (a) The basic principle behind sputter coating is that ions of an inert gas are fired at a block of the desired source material (the target) under vacuum. An incident ion passes its kinetic energy to atoms at or near the target surface, allowing them to escape into the vacuum. The substrate to be coated is placed a short distance away from the target. Any released atoms hitting the substrate will condense and form the desired coating. In order to achieve this, in the case of rf magnetron sputtering, the sample and metal target are mounted inside a vacuum system. Argon gas is injected into the chamber, and an rf electric field is then applied to the target. This causes a plasma to be generated which contains argon ions. The bulk of the plasma is at a positive potential relative to the target due to the plasma sheath, and so the Ar^+ ions are accelerated towards the target, leading to sputtering and the formation a metallic thin film. Rf electric fields are not screened by insulators, and so the metal target may be replaced by a metal oxide or metal nitride target to produce these materials. Alternatively, the addition of oxygen or nitrogen to the argon gas supply causes the surface of a metal target to become oxidised (or nitrided) allowing sputtering of the relevant material. This process is called reactive sputtering. A schematic diagram is shown in Fig.1. [30%]

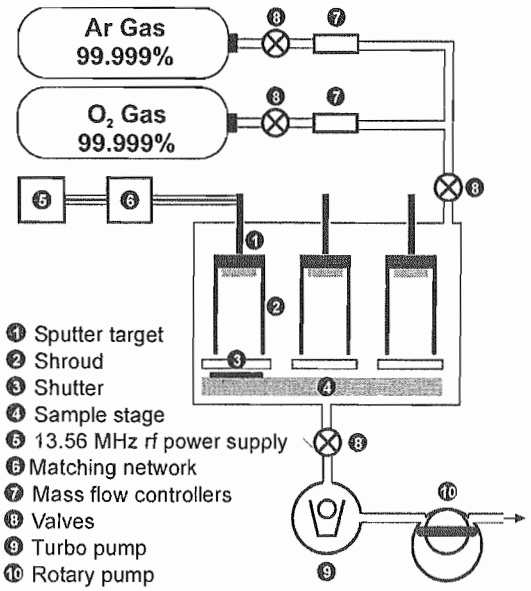


Fig.1 [10%]

(b) The sputter yield is defined as the number of atoms removed per incident ion. [5%]

(c)

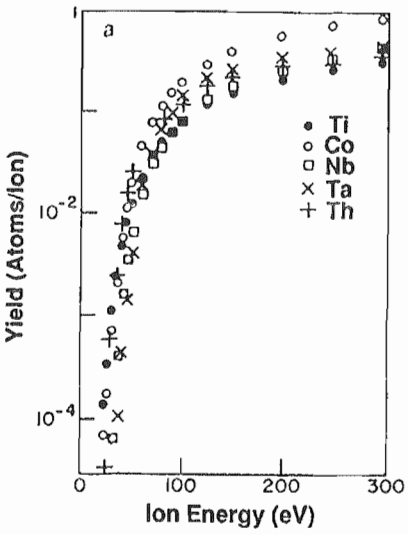


Fig. 2 [10%]

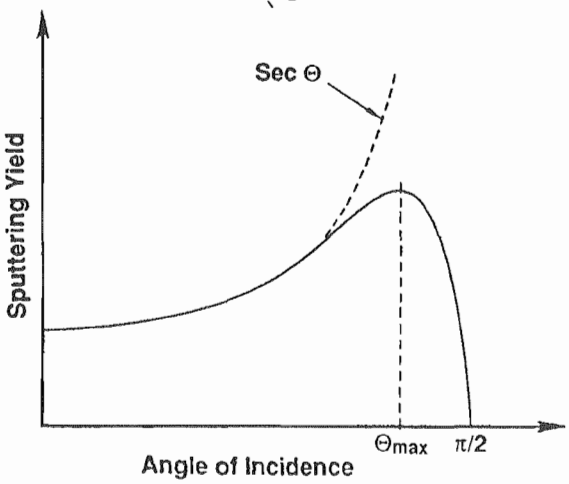


Fig. 3 [10%]

In order to impart a significant kinetic energy to the target, a relatively massive inert gas atom is required, and Ar is most frequently employed. [5%]

(d) In sputtering, the sample is exposed to the plasma, and therefore suffers bombardment by the Ar^+ ions. Ion bombardment tends to lead to high compressive stresses due to the incorporation of additional atoms into the crystal structure. Intrinsic stresses are particularly important in MEMS devices as they can lead to mechanical distortion of structure or eventually delamination of different material layers that should be in contact with each other. [20%]

(e) In lift-off patterning, it is important that the side walls of the photoresist are exposed so that the etching chemical for the resist can reach the material to be removed. Thermal evaporation produced highly non-conformal coatings, and so side walls of the resist would remain metal free, whereas sputtering produces more conformal coatings. Therefore, there is a risk of the photoresist becoming completely coated by sputtering, preventing successful lift-off. [10%]

3 (a) The direct bonding of two silicon wafers occurs by a three step process: wafer preparation, fusion and annealing. Initially the surfaces of the two wafers must be prepared for mating. Both surfaces must be cleaned and hydrophilised so that water molecules chemisorb onto the two surfaces. This is normally achieved by wet cleaning followed by a dry plasma hydrophilisation. A major concern in all bonding processes is the presence of voids caused by non-contacting areas due to particles, organic residues, surface defects and inadequate mating. Aligned mating must be performed in a particle free environment with good control of the mechanical contact (which is complicated by surface patterns). The two wafers are then brought into mechanical contact and adhere via hydrogen bridge bonds between the surface water molecules. Natural wafer bow normally allows contact to be initiated in the centre of the wafer from where it spreads out radially. Post-fusion annealing is required to increase the strength of the bond by causing the water molecules on the internal surface to form Si—O—Si bridge bonds. In general, the bonding strength increases with annealing temperature, and it is normally the presence of other materials which limits the temperature employed. Metallised wafers cannot normally be heated above 450° C otherwise the metal may melt. Diffusion or implantation doped wafers cannot normally be heated above 800° C without allowing further unwanted dopant migration. Ideally, a temperature of above 1000° C applied for several hours should be used to ensure maximum bond strength. [30%]

Wafer bonding is particularly important in MEMS devices, as bulk micromachining techniques, such as DRIE or KOH etching, really only allow 2.5D structures to be fabricated as the masking pattern on the surface is simply being transferred down through the bulk of the material. Wafer bonding allows genuinely 3D structures to be fabricated, such as the MIT microengine, which required six wafers to be bonded together to realise the complex 3D structure of the device. [10%]

(b) The process flow is as follows:

Step	*Code*	*Description*	
1	RCA1	Boil the silicon substrates in RCA Clean 1 (NH3(aq):H2O:H2O2) to remove organic contaminants.	
2	RCA2	Boil the silicon substrates in RCA Clean 2 (HCl:H2O:H2O2) to remove metallic ion contaminants.	[5%]
3	SOL1	Solvent clean the glass substrate in an ultrasonic bath of each of the following chemicals for ten minutes sequentially: acetone, isopropanol, DI water.	[5%]
4	BAK1	Bake the glass substrate for 30 minutes at 125 °C to dry.	
5	EVA1	Thermally evaporate a 50nm thick layer of aluminium onto the bottom side of the glass.	[5%]
6	MAL1	Mallory bond one silicon wafer onto the top side of the glass, using the thermally evaporated Al layer as one contact for the bonding process and the silicon wafer for the other.	[5%]
7	ALE1	Remove the aluminium layer by dipping the bonded glass and silicon wafer into proprietary aluminium etch.	[5%]
8	DIW1	Rinse the bonded glass and silicon wafer in DI water.	
9	BAK2	Bake the bonded glass and silicon substrate for 30 minutes at 125 °C to dry.	
10	SIN1	Deposit a 300 nm layer of SiN onto the top surface of the unbonded silicon wafer by LPCVD.	[5%]
11	PHO1	Spin a layer of photoresist onto the top surface of the sample wafer. The photoresist should be thick compared with the thickness of the SiN.	
12	BAK3	Pre-bake the photoresist.	
13	EXP1	Expose the photoresist through a mask to produce an array of 6 μm diameter dots with each dot centred on where a silicon tip will be.	
14	DEV1	Develop the photoresist.	
15	BAK4	Post-bake the photoresist to harden it.	[5%]
16	RIE1	Use reactive ion etching in a CF_4+O_2 plasma to remove the exposed SiN.	[5%]
17	ACE1	Rinse the substrate in acetone to remove the remaining photoresist.	
18	TOX1	Thermally oxidise the top 3 μm of the silicon wafer by heating in an wet oxygen environment to ~1000 °C. The silicon nitride dots will protect the underlying silicon from oxidation, although isotropic oxidation under the dots will take place.	[5%]

19	RIE2	Use reactive ion etching in a CF_4+O_2 plasma to remove the remaining SiN.	[5%]
20	HFE1	Dip the silicon substrate in buffered HF solution to etch away the oxide. This will leave silicon tips centred on the location of the SiN dots.	[5%]
21	DIW2	Rinse the bonded glass and silicon wafer in DI water.	
22	BAK5	Bake the bonded glass and silicon substrate for 30 minutes at 125 °C to dry.	
23	MAL2	Mallory bond this silicon wafer onto the under side of the glass in vacuum, using the two silison wafers as the anode and cathode.	

4 (a) A diagram showing the three photolithographic printing techniques in shown in Fig. 4.

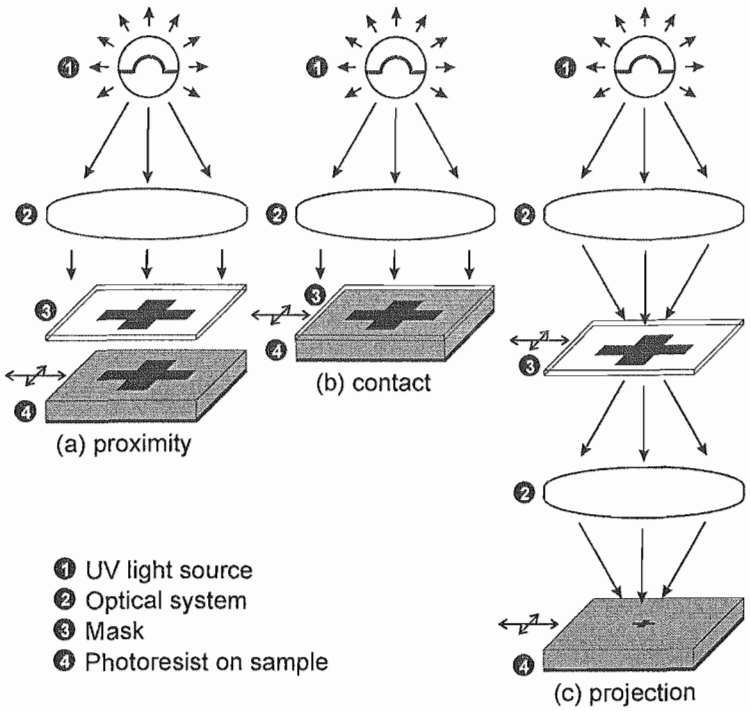


Fig. 4

(i) In proximity printing the light from a UV lamp is collimated and passed through a plate of glass (the mask) which has a 1:1 copy of the pattern to be printed as a metallic layer on the lower side. The metal pattern casts a shadow onto the photoresist coated substrate which is held parallel to the mask a small distance below is (known as the proximity or printing gap). The metallic pattern casts a shadow onto the substrate causing only certain areas of the photoresist to be exposed to the UV light and either weakened or hardened. The critical dimension is limited by the near-field diffraction of light around the opaque features in the mask. [15%]

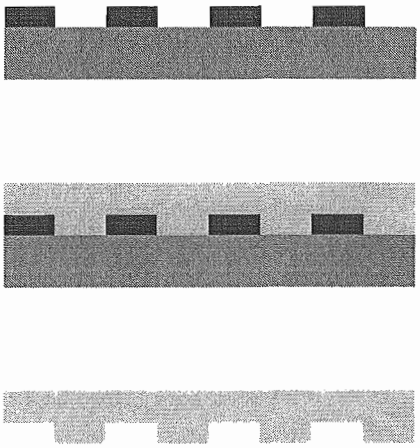
(ii) Contact printing is almost identical to proximity printing, except that the mask and substrate are held in contact and a pressure applied between the two. With a reduced distance between the mask and the photoresist, the diffraction

of the light is reduced, and hence finer structures may be produced. However, contact printing can lead to long-term damage to the mask. [15%]

(iii) In projection printing, the light from a UV is passed through the mask which now contains an enlarged version of the pattern to be printed. Optics is used to project the pattern on the mask down onto the substrate, which is some distance below. The position of the substrate is then scanned relative to the mask so that the same pattern is repeated many times over the substrate. Once again, it is the diffraction of light that limits the critical dimension, but this is now a far-field diffraction, and so the Rayleigh criterion may be used to determine the resolution that can be achieved. Projection printing has the advantage that the mask can be at a courser resolution than the pattern to be produced, but suffers from the fact that the same pattern must be repeated all over the substrate, and the cost of the projection optics is high. [15%]

(b) (i) In microcontact printing, a solution containing the material to be patterned is produced. A PDMS stamp which has raised regions where the material is to be deposited is dipped into the solution. The stamp is then pressed onto the substrate to be coated. This has the advantage that exceptionally high resolution features can be produced (down to a few tens of nm) as resolution is no longer limited by the diffraction (and hence the wavelength) of light. [15%]

(ii) The process flow for producing the stamp is shown in Fig. 5. It should be noted that PDMS is hydrophobic in its native state, but may be made hydrophilic by exposure to an oxygen plasma which leaves OH groups on the surface.



1 Photoresist is patterned onto a silicon substrate in the negative of the pattern to be printed. The surface is then treated with (tridecafluoro-1,1,2,2-tetrahydrooctyl)-1-trichlorosilane to reduce adhesion.

2 PDMS (polydimethylsiloxane) is spin coated over the patterned resist and cured at 60° C for one hour.

3 Finally, the PDMS may be simply peeled away from the substrate to leave the printing stamp.

Fig. 5 [20%]

(iii) Reducing cost is particularly important where the finished device has little material value. Microfabrication, however, tends to be a high cost technology that is better suited to high-end, high value devices (microprocessors, memory, etc.). Therefore, to make low value devices economic, the processing costs must be significantly reduced. A good example are disposable devices for medical applications, which must be produced for a few pence in order to be economically viable, such as glucose sensors. Microcontact printing is a low cost patterning technology, and may be used to functionalise cantilevers for biological sensors, for example. [20%]