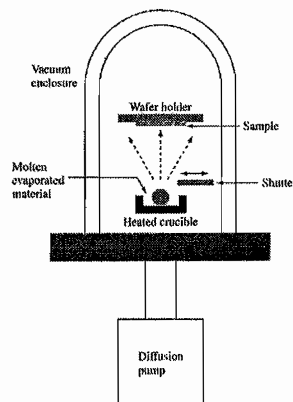
1 (a) Thermal evaporation is a popular method for producing thin metallic layers due to its simplicity. The metal to be deposited is placed on a metal filament (normally W or Mo with a much higher melting point) inside a vacuum chamber which is held at a pressure below 10^{-4} Pa. A current is passed through the filament, which heats up causing the metal to evaporate. [15%]

A high vacuum is required in thermal evaporation to ensure than contamination of the metal layer is minimised. The source to substrate distance should be small compared with the mean free path in the vacuum. The time required for a monolayer of the residual vacuum material to hit the substrate surface should be long compared with the time for a monolayer of material to be evaporated. [5%]

Evaporation results in 'line of sight' deposition from what is essentially a point source of evaporating metal. Evaporation therefore gives very poor step edge coverage, which is frequently a problem (although can occasionally be put to good use) and films are non-uniform over large areas. Evaporation produces generally amorphous metallic layers, frequently with a high surface roughness. The kinetic energy associated with depositing atoms is very low (~0.1 eV) so there is little possibility of damage to underlying layers, although thermal damage from the filament should be considered [10%]



[10%]

(b) We know that the thickness of the evaporated film will decrease towards the edge of the substrate as

$$R \sim \frac{\cos^2 \theta}{d^2}$$

from equation 5.3 of the *4M6 Data Book*. If h is the separation of the filament and substrate, then

$$\cos\theta = \frac{h}{d}$$

If the diameter of the substrate is ϕ, then the thickness of material at the edge of the substrate is

$$R_\phi \sim \frac{\cos^2\theta}{d^2} = \frac{h^2}{d^4} = \frac{h^2}{\left(h^2 + \phi^2/4\right)^2}$$

while at the centre of the substrate,

$$R_0 \sim \frac{1}{h^2}$$

The uniformity is then

$$U = \frac{R_\phi}{R_0} = \frac{h^4}{\left(h^2 + \phi^2/4\right)^2} = \frac{300^4}{\left(300^2 + 100^2/4\right)^2} = 0.9467 \qquad [15\%]$$

Hence, the thickness of the aluminum film at the centre of the substrate, t, when it is 100 nm at the edge will be given by

$$t = \frac{100\ \text{nm}}{U} = 105.6\ \text{nm} \qquad [10\%]$$

Assuming that the aluminium is evaporated uniformly over a hemisphere above the filament, then the volume of aluminium required will be

$$V = \frac{4\pi d^2}{2} t = \frac{4\pi \cdot 0.3^2}{2} 105.6\times10^{-9} = 5.972\times10^{-8}\ \text{m}^3 \qquad [10\%]$$

[NOTE: assuming over a full sphere would also be acceptable, doubling the results.]
Finally, then, the mass required is

$$m = \rho V = 2643 \cdot 5.972\times10^{-8} = \underline{158\ \text{mg}} \qquad [10\%]$$

(c) Alternative methods include (any two of) electron beam heating, laser heating (both of which have the advantage of reduced contamination as the crucible is not significantly heated) and rf induction heating (which has the advantage of not requiring the heated filament). A description of each method is given in the course notes. [25%]

2 (a) The resonant angular frequency ω is given by

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

where m is the lumped mass, which we will assume to be equal to the mass of the cantilever. Substituting for k in this expression gives

$$\omega^2 = \frac{Ewh^3}{4l^3 m} = \frac{Ewh^3}{4l^3(\rho whl)} = \frac{Eh^2}{4l^4 \rho}$$

$$\therefore \omega = \sqrt{\frac{E}{\rho}} \cdot \frac{h}{2l^2}$$

and so the figure of merit is that $(E/\rho)^{1/2}$ and h/l^2 must be maximized. [35%]

(b) Silicon carbide would be a good choice of material as it can be deposited by chemical vapour deposition in a thin film (the other alternative materials are all ceramics which would be difficult to fabricate into a cantilever). There should also be good etching selectivity between this material and the underlying silicon substrate. Plasma enhanced chemical vapour deposition would be possible using a gas mixture of silane and methane. Silicon nitride would be an acceptable alternative material, also deposited by LPCVD with a SiH_2Cl_2 and NH_3 gas mixture. [30%]

(c) Using the data for silicon carbide from the Material Property Charts, we know that the Young modulus is 400 GPa and the density is 3000 kg m^{-3}. Hence,

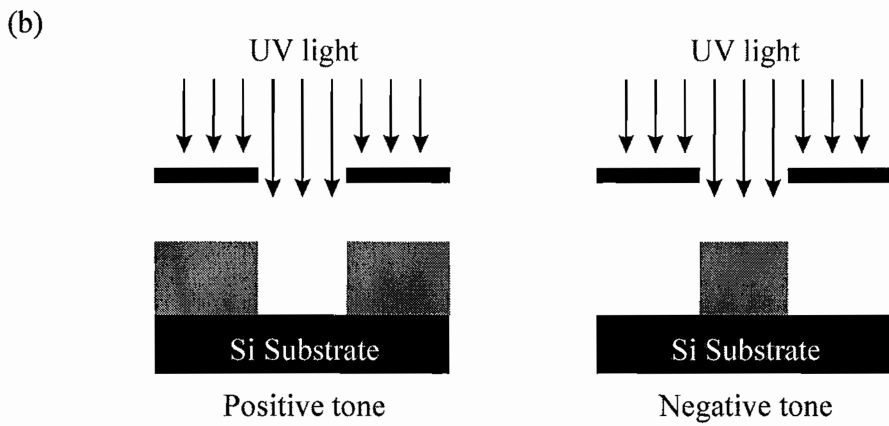
$$\frac{h}{l^2} = 4\pi f \sqrt{\frac{\rho}{E}} = 4\pi \cdot 20 \times 10^6 \sqrt{\frac{3000}{400 \times 10^9}} = 11970$$

Selecting film thicknesses between 0.5 and 1.0 μm would be reasonable, giving cantilever lengths between 6.5 and 9.1 μm. The width is a fairly free parameter, but it would be sensible to choose something smaller than the length (to avoid the plate modulus becoming

dominant) and yet not too thin as to make processing difficult, so ~2 μm would be appropriate. [35%]

3 (a) A photoresist is an organic polymer resin, (with a sensitiser) in a liquid solvent. In the case of positive tone photoresists, exposure of the resist to high energy photons in the deep UV causes scission of the polymers chains. The weakened polymer may then be removed by a developer solution (usually a weak base, such as KOH) in the exposed region. In the case of negative tone photoresists, however, exposure of the resist either causes cross-linking of the polymer chains to create large molecular weight chains which are insoluble, or induce a photochemical change to an insoluble polymer. Positive tone resists tend to achieve higher resolutions and have greater sensitivity than negative resists, but suffers from poorer adhesion. [30%]

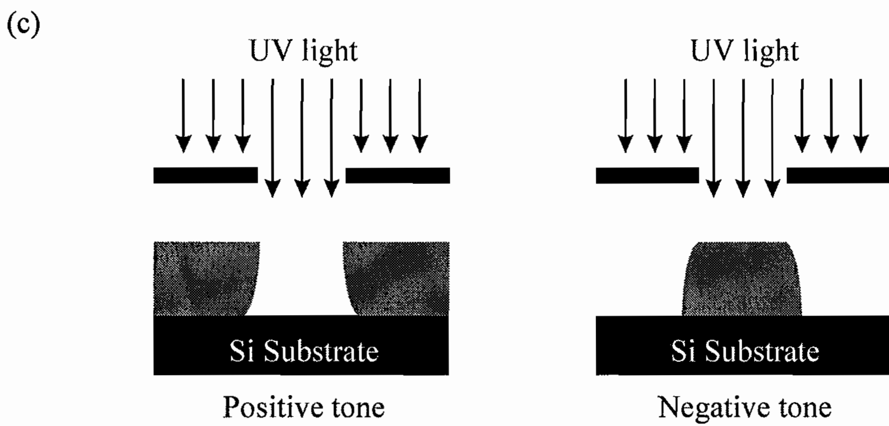
(b)



[20%]

Fig. 1

(c)



[20%]

Fig. 2

(d) From equation 9.5 of the *4M6 Data Book*, in order to achieve a 0.6 μm resolution,

$$z = \frac{8R^2}{9\lambda} = \frac{8\left(0.6\times10^{-6}\right)^2}{9\cdot190\times10^{-9}} = 1.7\ \mu\text{m}$$

Therefore, a spin speed of 2800 rpm will be required. [30%]

4 (a) Yield is the number of devices or component parts produced as a fraction of the expected number given the amount of incoming materials and devices processed. [10%]

(b) Factors that can affect yield include achieving designed tolerances in processes (by controlling critical etching times and profiles; resolution and alignment in photolithography; material quality, surface roughness and reproducibility and critical deposition times), quality of interfaces by controlling environment between processing of layers), quality of bonds and interconnects, stress (by minimizing residual stress and stress gradients), stiction (by controlling wet etches), particle contamination, fracture, gross errors such as incorrect tool settings and poor packaging. Yield can always be improved by identifying yield-critical steps and front-loading them in the processing and designing recovery processes in the event of failure. [30%]

(c) Process flow:

i) Si(100) wafer.

ii) RCA1 Clean – removal of organic contaminants on Si wafer.

iii) RCA2 Clean – removal of metal ion contaminants on Si wafer.

iv) LPCVD SiN – low pressure chemical vapour deposition of silicon nitride using a gas mixture of SiH_2Cl_2 and NH_3 at 800° C to produce a 400 nm thick layer.

v) Positive photoresist – spin on photoresist (thickness should be at least $690/1300 \times 400$ nm = 212 nm, but in practice we will use a much thicker layer) to a thickness of 1 μm.

vi) Photoresist pre-bake – removal of solvent.

vii) Mask 1 – exposure of photoresist to UV light through pattern of the SiN cantilevers (alignment of edges to [110] direction).

viii) Photoresist development.

ix) Exposure to CF_4+CHF_3+He (10:5:10 sccm) plasma for (at least $400 / 130 \times 60 =$) 200 s to remove SiN.

x) Strip photoresist – in acetone ultrasound bath.

xi) Cr evaporation – thermal evaporation of the 100 nm thick chromium layer.

xii) Positive photoresist – spin on photoresist (assume not etched in Cr etch later, so no minimum thickness requirement) to a thickness of 1 μm.

xiii) Photoresist pre-bake – removal of solvent.

xiv) Mask 2 – exposure of photoresist to UV light through pattern of the chromium track aligning with the SiN structure defined.

xv) Photoresist development.

xvi) Cr etch – etch of exposed chromium to proprietary Cr etch.

xvii) Strip photoresist – in acetone ultrasound bath.

xviii) KOH etch – etch in 33% KOH solution at 80° C using the SiN structure as a hard mask for (20000/150 =) 133 minutes to achieve 20 μm air gap.

xix) Rinse in DI water.

xx) Rinse in isopropanol.

xxi) Rinse in acetone.

xxii) Dry. [50%]

The final rinsing and drying is most likely to reduce yield due to the dangers of stiction. Rinsing must be very thorough to ensure no water remains in the final drying stage. Freeze releasing might also be considered to improve yield. [10%]