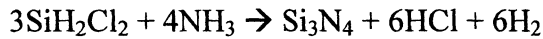
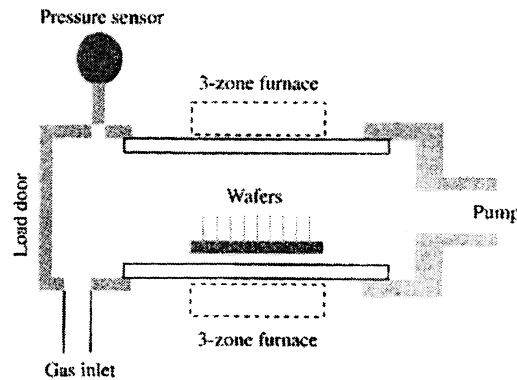


4M6 Materials and Processes for Microsystems (MEMS)**Exam Crib 2005**

1 (a) Low pressure chemical vapour deposition (LPCVD) tends to be preferred for the deposition of silicon nitride (a-SiN). In this case a mixture of SiH_2Cl_2 and NH_3 is fed into a chamber. The gases are extracted by a vacuum pump which allows a low pressure of ~ 70 Pa to be maintained. The substrates to be coated are stacked vertically and heated to $\sim 800^\circ\text{C}$. This temperature is sufficient to thermally induce a chemical reaction on the surface of the substrate forming a-SiN by



In this way a layer of silicon nitride grows conformally on the substrate surface. A schematic diagram of the system is shown below.



(b) From the Stoney equation (*4M6 Data Book*, Section 2.10),

$$\sigma = \frac{E}{6(1-\nu)} \frac{t_s^2}{t} \left(\frac{1}{R_c} - \frac{1}{R_0} \right) \quad (8.7)$$

Before deposition, the wafer is flat, and so $1/R_0 = 0$ m. Hence, the Stoney equation simplifies to

$$\sigma = \frac{E}{6(1-\nu)} \frac{t_s^2}{t} \frac{1}{R_c}$$

From Section 1.1 of the *4M6 Data Book*, the Young Modulus of the substrate, $E = 190$ GPa and the Poisson ratio $\nu = 0.22$. Hence,

$$\sigma = \frac{190 \times 10^9 \cdot (450 \times 10^{-6})^2}{6(1-0.22) \cdot 500 \times 10^{-9} \cdot 29 \cdot 90}$$

$$\sigma = 550 \text{ MPa}$$

Assuming that all of the error is in the measurement of the two thicknesses, then

$$\left(\frac{\delta\sigma}{\sigma}\right)^2 = \left(\frac{\delta t}{t}\right)^2 + 2\left(\frac{\delta t_s}{t_s}\right)^2$$

The curvature of the stylus trace shows that the silicon nitride is under compressive stress. Therefore, this gives the final result that

$$\underline{\sigma = (550 \pm 70) \text{ MPa compressive}}$$

(c) Stress minimisation is of prime importance in MEMS devices as it can lead to unintentional structural deformation. In the case of a highly stressed material in intimate contact with a substrate, the system will bow. At a critical thickness, the stressed material can delaminate from the underlying substrate, as it represents a lower energy to create a new surface between the materials and relieve the stress of the system. For a material with a stress gradient (where stress varies with depth into the material) then free standing structures made with this material will also bow out of plane.

(d) Stoichiometric silicon nitride tends to have a high tensile stress. However, this stress may be reduced by increasing the silicon content of the material. This can be achieved by increasing the flow rate of dichlorosilane relative to ammonia flowing into the deposition chamber.

2 (a) *Piezoelectric effect*: Certain materials (such as quartz) have the physical property that a charge is developed on their surface when a mechanical stress is applied to them. Vice versa, it is also true that when a voltage is applied between two surfaces of a piezoelectric, a mechanical stress is generated. We can think of the piezoelectric effect as being due to the movement of anions and cations within the material under the influence of an applied electric field. The presence of both strong and weak ionic bonds in noncentrosymmetric crystals (with a lack of central symmetry) produces a deformation of the lattice. Piezoelectrics are extremely useful for MEMS applications as they provide a direct link between electric and mechanical properties,

$$D = d\sigma + \varepsilon_0 \varepsilon_r \Big|_{\sigma} E \quad (6.33a)$$

$$D = e\varepsilon + \varepsilon_0 \varepsilon_r \Big|_{\varepsilon} E \quad (6.33b)$$

Piezoresistive effect: The effect that the resistivity of a material can change when a mechanical stress is applied to a material is known as piezoresistivity. This phenomenon is caused by the change in the atomic spacing in the crystal lattice under deformation. The periodic potential produced by the atomic lattice has a profound effect on the electrical properties of a material and most notably that of semiconductors. It is therefore perhaps unsurprising that changing this series of potential wells by the application of a stress will change the resistivity. This is particularly useful for MEMS sensors as it provides a useful means of electrically detecting mechanical strains. Assuming piezoresistance to be linearly dependent on stress (which is true for small strains) we can rewrite the Ohm Law as

$$\mathbf{E} = [\rho_e + \mathbf{\Pi} \cdot \boldsymbol{\sigma}] \cdot \mathbf{J} \quad (6.38)$$

where ρ_e , $\mathbf{\Pi}$, $\boldsymbol{\sigma}$ and \mathbf{J} are the resistivity, piezoresistive, stress and current density tensors.

Shape memory effect: Certain metal alloys, such as NiTi also display a shape memory effect. These alloys all undergo a crystalline phase transformation from a weak and easily deformable state at low temperatures to a hard phase at temperatures above a transition temperature, T_{tr} . Initially, the material is held in the desired shape and heated to above T_{tr} to fix this shape ‘in memory’. The material is then allowed to cool into its weak state, when it can be deformed easily. However, upon heating the alloy above T_{tr} once more, it reverts to its ‘stored’ shape, exerting very large forces in the process, making these materials very useful as mechanical actuators in situations where a high frequency response is not required.

(b) X-ray diffraction provides the most effective means of determining crystal structure. In particular, this technique provides excellent resolution between amorphous and crystalline phases. The wavelength of X-rays is of a similar length scale to the interatomic spacing. Different crystal structures therefore produce well-defined diffraction peaks at particular angles. The polycrystalline silicon will therefore produce bright spots that lie in circles at a particular angle. Amorphous silicon will, however, produce diffuse diffraction rings. Therefore, if the material is fully crystallised then these diffuse rings will be absent from the X-ray diffraction pattern. It should be noted that Raman spectroscopy is also sensitive to the

amorphous and crystalline phases of silicon, with amorphous material producing a broad Raman peak at $\sim 480 \text{ cm}^{-1}$, whereas crystalline material will produce a sharp peak at close to 510 cm^{-1} , and so this may also be used to determine whether the material is fully crystallised.

3 (a) A major yield problem which is fairly specific to microsystems is stiction. This becomes a problem for devices that have suspended mechanical components over an air gap. Stiction occurs when some force causes the mechanical collapse of a suspended structure. In the case of wet chemical processing, it is the capillary force which causes collapse of the suspended structure. Liquids with a high surface tension will attempt to minimise energy by collapsing the suspended structure – essentially the pressure inside the liquid is lower than outside. The structure then adheres to the underlying substrate.

(b) (i) The critical contact point is the distance below which there is always sufficient elastic energy in the cantilever to release the structure. Therefore, a long cantilever which has adhered to the substrate should manage to release itself out to a distance s^* .

(ii) The energy associated with adhering the cantilever to the surface beyond distance s is given by

$$U_s = -\gamma b(L - s).$$

The total energy of the system is then

$$U_T = U_E + U_s = \frac{Ebh^3g^2}{2s^3} - \gamma b(L - s).$$

The critical contact point occurs at the turning point of this curve, so

$$\frac{\partial U_T}{\partial s} = -\frac{3Ebh^3g^2}{2s^4} - \gamma b = 0.$$

Hence,

$$s^* = \left(\frac{3Eh^3g^2}{2\gamma} \right)^{1/4}.$$

For the cantilever of Fig. 2,

$$s^* = \left(\frac{3.190 \times 10^9 \cdot (0.5 \times 10^{-6})^3 \cdot (40 \times 10^{-6})^2}{2.0 \cdot 3} \right)^{1/4}.$$

$$\underline{s^* = 117.4 \mu\text{m}}$$

(iii) The cantilever should be designed to be shorter than the critical contact length so that there is always sufficient elastic energy to completely release the structure from the substrate.

(iv) We can try to change the beam geometry to ensure that the beam length is less than s^* by increasing thickness and support height. The contact

areas may be reduced by texturing the area between the cantilever and the substrate. Alternatively, we could try to reduce the surface energy of the system by applying a low energy coating to make the surface hydrophobic using self assembled monolayers (SAMs) or a low surface energy materials, such as diamond-like carbon.

4 (a) An etch stop is a transition in material properties (usually a complete change in material itself) at a certain plane that will cause a significant change in the rate at which either a wet or dry etch proceeds. This will cause the etch process to effectively stop on this plane surface. In this way, very precise thicknesses of material may be removed by an etch process. Etch stops are therefore employed when features of a particular depth are required to be created.

(b) Process flow is as follows:

I RCA1 Clean

Removal of organic surface contaminants from the wafer.

II RCA2 Clean

Removal of metal ion contaminants from the wafer.

III 2 μm Silicon Dioxide sputter deposition

Sputtering is probably best here as high electronic quality is not necessary, and the subsequent metal layer can also be sputter deposited, so a break of vacuum will not be required, improving cleanliness. Thermal oxidation is possible, but would be very slow. PECVD is also acceptable.

IV 100 nm Titanium sputter deposition

Sputter deposition of titanium in the same system as the previous silicon dioxide layer. Thermal evaporation is also possible.

V 1.5 μm Positive Photoresist formation (spin & prebake)

1.5 μm positive resist will comfortably permit 2 μm features to be produced, as required for formation of the heating element tracks. Photoresist is not etched by Ti etch (see Section 2.15 of the *4M6 Data Book*) so there is no minimum thickness requirement to withstand the subsequent etch process. Positive resist used so that metal mask will not obscure most of the substrate.

VI Photoresist Exposure and Development

VII Titanium Etch

About 10 seconds required using proprietary etch.

VIII Photoresist Removal

Removal of photoresist using acetone ultrasonic bath. This is followed by an ultrasonic rinse in IPA and DI water.

IX 2 μm Silicon Dioxide sputter deposition

X 100 nm Titanium sputter deposition

This will be used to protect the reaction chamber from the silicon dioxide etch. Titanium is not etched by the RIE described in Step XVII, and so 100 nm is sufficient.

XI 1.5 μm Positive Photoresist formation (spin & prebake)

This is to pattern a protective hard mask over the 80 \times 80 μm encapsulated reaction chamber. The same requirements as in Step V apply.

XII Photoresist Exposure and Development

XIII Titanium Etch

About 10 seconds required using proprietary etch to remove all titanium except that protecting the future 80 \times 80 μm reaction chamber.

XIV Photoresist Removal

Removal of photoresist using acetone ultrasonic bath. This is followed by an ultrasonic rinse in IPA and DI water.

XV 41 μm SU8 Photoresist formation (spin & prebake)

A plasma etch will be required for the silicon dioxide as wet HF etches will attack the underlying Ti. The $\text{CF}_4+\text{CHF}_3+\text{He}$ etch is appropriate. This removes SU8 at a rate of 220 nm min^{-1} and removes silicon dioxide at a rate of 470 nm min^{-1} . Hence, as $2 \mu\text{m}$ of oxide will have to be removed, an extra 936 nm of SU8 is required, so a $41 \mu\text{m}$ thick SU8 layer must be employed.

XVI Photoresist Exposure and Development**XVII Silicon dioxide etch**

$\text{CF}_4+\text{CHF}_3+\text{He}$ etch for $\sim 4' 20''$.

XVIII Titanium Etch

About 10 seconds required using proprietary etch to remove the titanium hard mask protecting the heated reaction chamber.