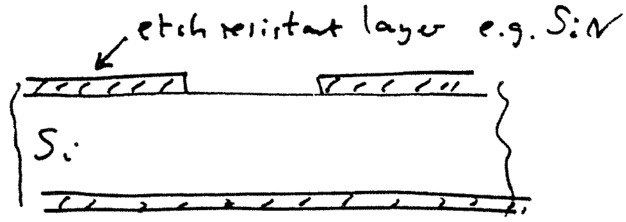
4C13 MEMS: Solutions

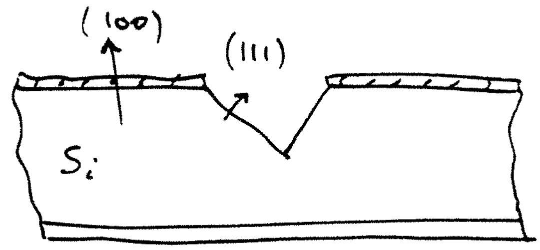
(a) Bulk micromachining is where the substrate itself (e.g. Si wafer) is etched to form part of the MEMS device.

conventional lithography and etching is used to pattern openings in the mask layer

Cross section

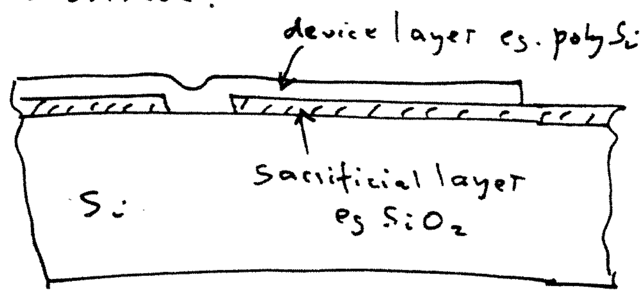


in the case of an anisotropic liquid etchant such as KOH the slow etching (111) silicon crystal planes are exposed after the etch process

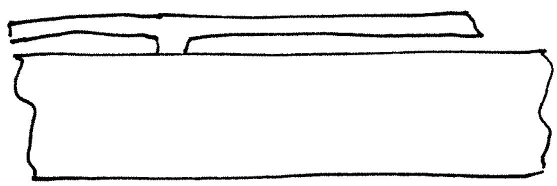


Surface micromachining involves the deposition of a sacrificial layer followed by a MEMS device layer on top of the silicon substrate.

again conventional lithography and etching is used to pattern both the sacrificial and the device layer.



after removal of the sacrificial layer eg. by etching in bHF the MEMS layer is suspended above the Si substrate and anchored to it where needed,



(b) MEMS acceleration sensors typically have a proof mass which flexes when the substrate suffers an acceleration, and a capacitative readout mechanism to detect the new position of the proof mass.

The surface micromachined ADXL accelerometer is the most

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successful low cost product partly because
- the readout electronics are integrated into the same BiCMOS chip which reduces manufacturing costs and improves reliability
- the fabrication process involves the smallest feasible number of changes from conventional CMOS – easier to introduce the technology.

more sensitive devices with a larger proof mass are made using bulk micromachining – in some cases involving several silicon substrates which are bonded together.
this gives a larger manufacturing cost and potentially lower reliability but allows much greater flexibility in MEMS device configuration.

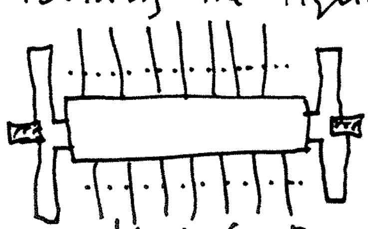
(c) the physical scaling laws result in self mass having less significance than for example surface effects when conventional devices are scaled down 100x into the MEMS regime.

If two freshly micromachined surfaces come into contact there is a strong possibility of them sticking together. This problem is potentially severe when the proof mass of a MEMS accelerometer is released because of the surface tension of the liquid etchants used in the process.

Either freeze drying is employed whereby the water solution is displaced by a solvent which is then frozen. MEMS release is achieved by sublimating the frozen material and avoiding the liquid phase.

Another way to avoid the effects of stiction is to support the proof mass with photoresist struts during MEMS release and then plasma etch in oxygen to remove the resist ie avoiding the liquid phase.

plan view



each dotted line is a photoresist fence which does not block the passage of the bHF to remove oxide

2 In the fabrication of MEMS & MMAs there is a need to release active layers and so to overcome the effects of local adhesion or stiction. On the other hand processes such as wafer bonding depend on beneficial aspects of surface forces.

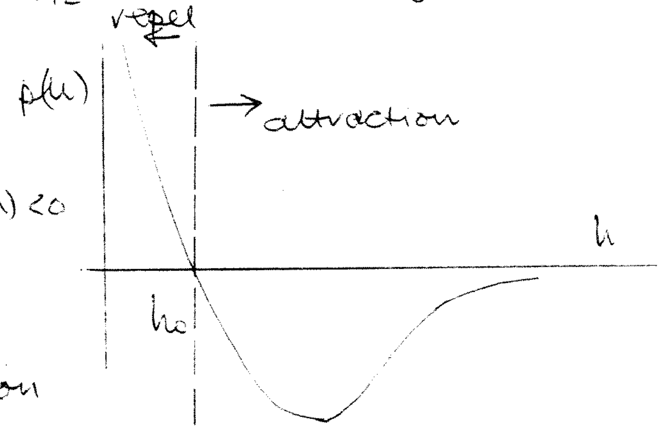
In operation adhesion can lead to the failure of comb drives and other forms of MEMS motors. When stiction and wear nutwest effects can lead to premature failure of MMA's.

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

when $h = h_0$ $p(h) \Rightarrow 0$ so surfaces are at equilibrium spacing.

w is "pull-off work" and $w = \gamma_1 + \gamma_2 - \gamma_{12}$

where γ_1 and γ_2 are surface energies of the two materials and γ_{12} is the surface energy of the interface.



Surfaces attract each other when $h > h_0$ i.e. $p(h) < 0$ and repel when $h < h_0$.

at point of max. attraction

$$\frac{dp(h)}{dh} = 0 \quad \text{i.e.} \quad \frac{8w}{3h_0}\left\{-\frac{3}{h_0}\left(\frac{h}{h_0}\right)^{-4} + \frac{9}{h_0}\left(\frac{h}{h_0}\right)^{-10}\right\} = 0$$

$$\therefore \quad 3\left(\frac{h}{h_0}\right)^{-4} = 9\left(\frac{h}{h_0}\right)^{-10} \quad \text{i.e.} \quad \left(\frac{h}{h_0}\right)^{6} = 3$$

$$\text{i.e.} \quad \left(\frac{h}{h_0}\right) = 3^{1/6}$$

at which point $p(h) = \frac{8w}{3h_0}\left\{3^{-1/2} - 3^{-9/6}\right\}$

$$= \frac{8w}{3h_0}\left\{\frac{1}{\sqrt{3}} - \frac{1}{3\sqrt{3}}\right\} = \frac{16w}{9\sqrt{3}\,h_0}$$

To pull surfaces apart will need tensile stress σ_{th} of this size

Elastic modulus $E = \dfrac{\text{increment of stress}}{\text{increment of strain}}$

i.e. $E = \left|\dfrac{d\,p(h)}{dh/h_0}\right|_{h=h_0}$

But $\left|\dfrac{d\,p(h)}{dh}\right|_{h=h_0} = \dfrac{8w}{3h_0}\left\{-\dfrac{3}{h_0} + \dfrac{9}{h_0}\right\} = \dfrac{16w}{h_0^2}$

and $\therefore \quad E = \dfrac{16w}{h_0}$

But $\tau_{th} = \dfrac{16w}{9\sqrt{3}\,h_0} \qquad \tau_{th} = \dfrac{16}{9\sqrt{3}} \cdot \dfrac{E}{16} = \dfrac{E}{9\sqrt{3}}$

i.e. $\tau_{th} \simeq 0.064\,E$

In practice adhesion is very much less than this due principally to the combined effects of surface topography and surface contamination.

Examiner's Comments

Q1 average mark 12.8/20; Max 18; min 7
Always difficult to get full marks on a qualitative question but most candidates produced reasonable answers.

Q2 average: 13.3/20; max 17; min 7
Straightforward question based on lecture material referring back to Part I.

Q3 average 13.5/20; max 19; min 6
Errors mostly algebraic rather than conceptual. Some candidates forgot that there are three vibs.

3. Dimensional argument shows that

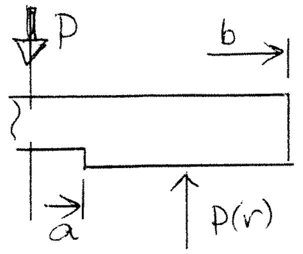
$$\tau_{inertia}/\tau_{adhesion} = \rho r \omega^2/\gamma$$

where ρ density, γ surface energy, r scale and ω speed.

Thus in moving from macro to micro scales, ρ, γ unchanged, r reduced by say 100 and ω increased by 30

So $\tau_{inertia}/\tau_{adhesion}$ reduces by factor $\frac{100}{30^2} \simeq \frac{1}{10}$

Thus in MEMS effects of stiction outweigh those of inertia



local pressure = $p(r)$, then local wear rate of Si will be proportional to $p(r) \times r\omega$

Since Si surface must remain flat wear rate must be independent of r

i.e. $p(r) = \frac{\alpha}{r}$ (say)

But $3\int_a^b p(r) c\, dr = P$, total load

So $3\alpha c \int_a^b \frac{dr}{r} = P$ i.e. $\alpha = \frac{P}{3c \ln(b/a)}$

So $p(r) = \frac{P}{3cr \ln(b/a)}$

Locally $\frac{dw}{dt} = K_w\, p(r) . r\omega$ $\qquad$ w = wear dimension

$= K_w \alpha \omega$

∴ Volumetric wear rate $= 3(b-a)c\frac{dw}{dt} = \frac{K_w (b-a)P\omega}{\ln(b/a)}$

∴ In one hour

$$\Delta V \Rightarrow \frac{2\times10^{-7}\times10^{-9}(100-30)10^{-6}\times5\times10^{-3}\times25000\times2\pi\times60}{\ln(100/30)} \; m^3$$

$= 5.48\times10^{-16}\ m^3$ or 548 micron^3

At radius r, frictional torque

$$dT = \mu r c\, p(r)\, dr = \mu c \alpha\, dr$$

$$T = \mu c \alpha \int_a^b dr \times 3$$

$$= \frac{\mu P(b-a)}{\ln(b/a)}$$

$$\Rightarrow \frac{0.16 \times 5\times10^{-3}(100-30)10^{-6}}{\ln(100/30)}$$

$$= 4.65 \times 10^{-8}\ \text{Nm}$$

For a given ω, P and K_w both ΔV and T depend on $\frac{(b-a)}{\ln(b/a)}$ so if $b = na$, then for a given value of a both vary with $\frac{n-1}{\ln n}$.

Since this increases with n, pays to make b as small as feasible.

In addition look at choice of materials to reduce K_w and μ. For example might it be possible to use DLC on one or both of rubbing surfaces? Effects of viscosity & surface tension will mean impossible to use conventional lubrication but relatively modest mean pressure $\bar{p}$ might make

($\bar{p} = 5\times10^{-3} \div (3\times 20\times(100-30)10^{-12}) = 1.2$ MPa)

protection by self assembled monolayer feasible.

Examiner's comments

Q4 average 12.2/20 max 16 min 7
Some confusion in estimating greatest etch depth and profile across MN.

Q5 average 13/20 max 17 min 9
Popular and well done by those completing the lab.

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Films are grown by vacuum evaporation. This method is widely applicable to a range of metals – but the deposited films are typically under tensile stress.

Sputter deposition is widely used in manufacturing for metal deposition and the stress can be controlled to some extent by adjusting the power and pressure and other sputter conditions.

Chemical vapour deposition (CVD) is used to manufacture dielectric films such as SiN SiO_2 etc. It is suited to mass production but is less adaptable than sputter deposition.

Spin on deposition followed by annealing is effective for depositing MEMS films such as PZT for actuators.

Ink jet deposition is becoming important and has the advantage that the deposited film can be directly patterned.

Wet etching using isotropic (eg. HF) or anisotropic (eg KOH) water based etchants is widely used in manufacturing.

Plasma etching (RIE) through a stencil mask gives more precise geometries and is widespread in manufacturing.

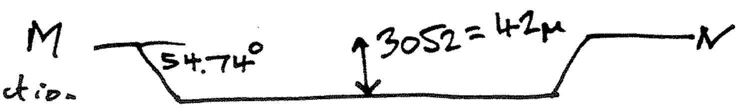
More specialized processes include laser etching which has the advantage in MEMS prototyping that a wide range of materials can be satisfactorally etched – but the throughput is less than RIE.

For more precise geometries focused ion beam etch is useful in MEMS prototyping because sub micron geometries can be cut and there is great flexibility in the shape of the cut. It may be applicable to trimming high value devices in manufacturing.

(b) (i) The orientation for minimum etching results in three separate terminated trenches. A is deepest, has two microbeams of SiC and the etch depth is $80\sqrt{2} = 113$ μm.

B and C are similar to each other with one beam each but a smaller depth

(ii) Cross section



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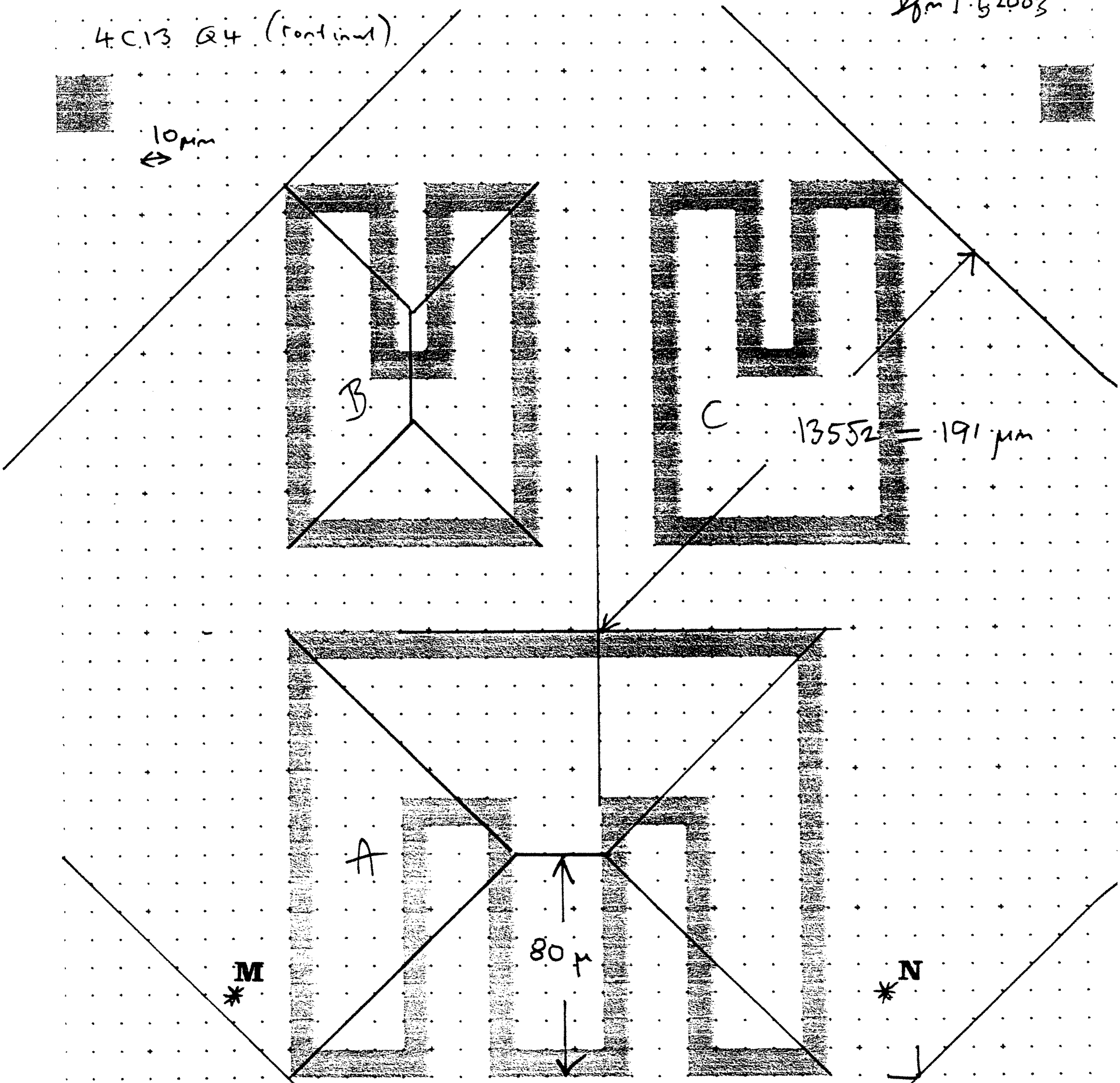


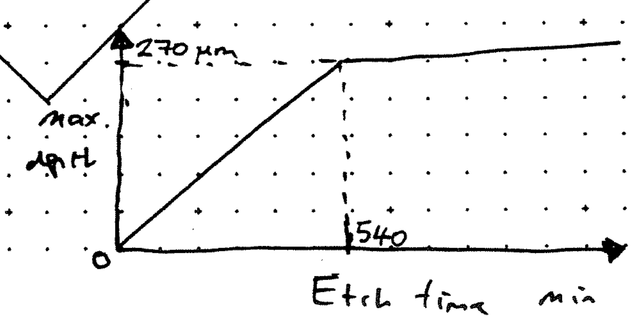
(iii) orientation to achieve the maximum depth results in one large hole which is an inverted pyramid.

The depth is $135\sqrt{2}\sqrt{2} = 270$ μm approximately [slight overestimate]

(iv) In this case the maximum depth increases at the rate of ~0.5 μm/minute until the nominal termination point is reached after which it increases by only 0.05 μm/minute.

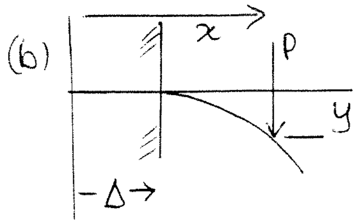
This assumes that the undercutting of the various convex corners is fast

In fact the change in increase rate occurs closer to the nominal maximum depth + 10%.



5 (a) Essentially bookwork & lecture notes. Examples of use of beams or flexures from such devices as accelerometers, optical displays, thermal motors etc.

(b)



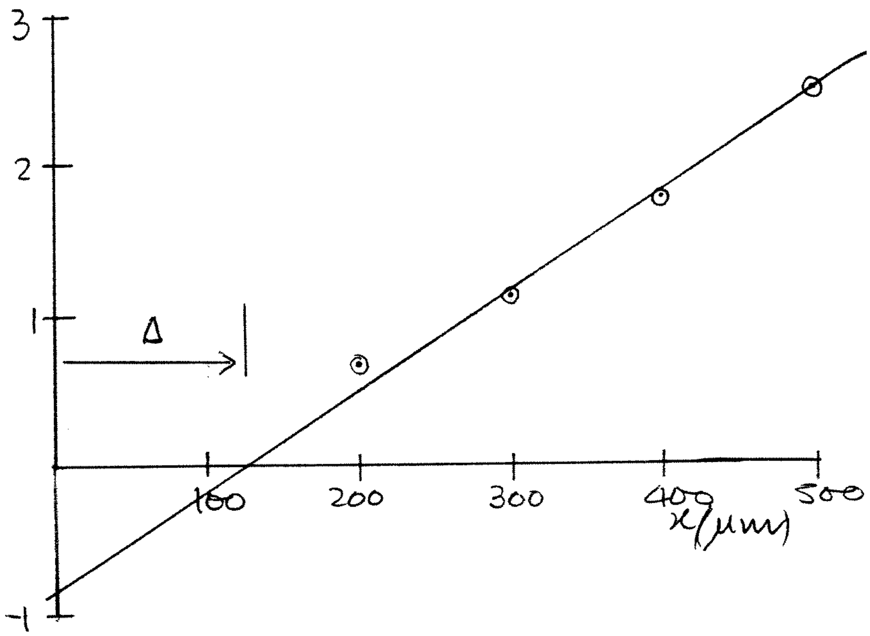
If beam within small deflection regime, but exact psn. of root unknown

$$y = \frac{P(x-\Delta)^3}{3EI}$$

$$\therefore \; y^{1/3} = \left(\frac{P}{3EI}\right)^{1/3} x - \left(\frac{P}{3EI}\right)^{1/3} \Delta$$

So plot $y^{1/3}$ vs x

x µm	200	300	400	500
y µm	0.3	1.5	5.7	15.7
$y^{1/3}$ µm$^{1/3}$	.67	1.14	1.79	2.50



from slope

$$\left(\frac{P}{3EI}\right)^{1/3} = \left(\frac{2.50}{375}\right) \mu m^{-2/3}$$

$$\frac{P}{3EI} = 2.96 \times 10^{-7} \; \mu m^{-2} \; (\mu m)^{1/3}$$

But $P = 400 \times 10^{-6}$ N

and $I = \frac{1}{12} bd^3$

$$= \frac{100 \times 5^3}{12} (\mu m)^4 = 1.042 \times 10^3 \; \mu m^4$$

$$\therefore \; E = \frac{400 \times 10^{-6}}{3 \times 1.042 \times 10^3 \times 2.96 \times 10^{-7}} \; N/\mu m^2$$

$$= 433 \text{ GPa}$$

$\Delta \sim 125 \mu m$

In addition to inaccuracies introduced by fitting to a limited no of points the numerical value very dependent on I and hence on d^3. Small error in d will be magnified in E.

JAW
May 03