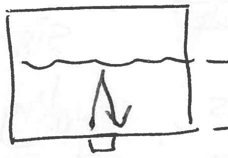
4B13 CRIB 2018

1(a)



Transit time for pulse-echo $= \frac{2\times 0{\cdot}65}{1324} + \frac{2\times 0{\cdot}003}{5960}$

$= 0{\cdot}983$ ms [10%]

(b)
$Z_{air} = 340$ Rayls
$Z_{oil} = \rho v = 1{\cdot}072$ M Rayls
$Z_{steel} = 45{\cdot}3$ M Rayls
$Z_{PZT} = 30{\cdot}0$ M Rayls
$Z_{water} = 1{\cdot}5$ M Rayls.

$P_{PZT} = V^2/R = 144/500 = 0{\cdot}288$ W

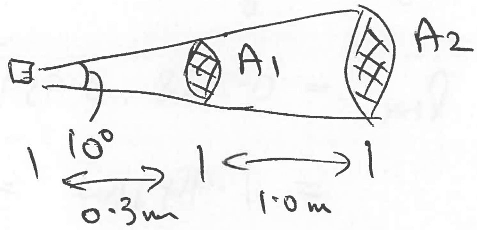
coupling PZT ⇔ steel $= \frac{4 Z_p Z_s}{(Z_p + Z_s)^2} = 0{\cdot}959$

coupling steel ⇔ oil $= 0{\cdot}090$

reflection oil ⇔ air $= \frac{(Z_o - Z_a)^2}{(Z_o + Z_a)^2} = 0{\cdot}999$

Attenuation over 1·3 m in oil = 0·91 dB = ×0·811
0·3 m in oil = 0·21 dB = ×0·953
6 mm in steel = 0·138 dB = ×0·969

Beam angle spread.



$A_1 = 21{\cdot}6\ cm^2$
$A_2 = 406\ cm^2$

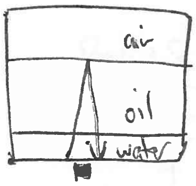
For 0·65 m, $P_{rec} = \frac{V_r^2}{R} = 0{\cdot}288 . 0{\cdot}959^2 . 0{\cdot}09^2 . 0{\cdot}999 . 0{\cdot}25^{-2}$
$\times 0{\cdot}811 . 0{\cdot}969 . \frac{\pi}{406} = 0{\cdot}815\ \mu W$

$\therefore V_r = 20{\cdot}2$ mV loaded = 40·4 mV open cct.

For 0·15 m, $P_{rec.} = 0{\cdot}288 . 0{\cdot}959^2 . 0{\cdot}09^2 . 0{\cdot}999 . 0{\cdot}25^2 . 0{\cdot}953$
$\times 0{\cdot}969 . \frac{\pi}{21{\cdot}6} = 18{\cdot}0\ \mu W$

[50%] ⇒ 0·095 V loaded ⇒ 0·19 V open cct

1 (c)



Coupling steel ⇔ water = 0·124

vs. 0·09 steel ⇔ oil so

Signal is larger by × 1·38

Extra reflection loss, coupling oil ⇔ water = 0·972

so net increase in ultrasonic power each way = × 1·34

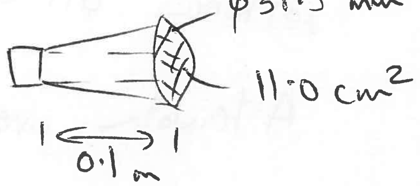
Transit time now: $\frac{2 \times 0.003}{5960} + \frac{2 \times 0.6}{1324} + \frac{2 \times 0.05}{1500} = 0.974$ ms

So, the net signal voltage will be larger by × 1·34 (34%) and the timing 99% (so the level indicated will be wrong – it actually partially compensates for oil being sat on a layer of water). Reads 64·4 cm apparent oil, but is of course only 60 cm of oil.

[20%]

(d) There will be a partial reflection from the oil-water interface of × 0·028. water atten = 0·0788 × 0·984

Beam area @ water/oil



Magnitude of oil-water reflection signal:

$P_{rec.} = 0.288 \,.\, 0.959^2 \,.\, 0.124^2 \,.\, 0.028 \,.\, 0.984 \,.\, \frac{\pi}{11} \Big/ 0.25^2$ (0.969)

$= 1.94\ \mu W = \frac{V_r^2}{R}$ ∴ V_r open cct = 62·3 mV water.

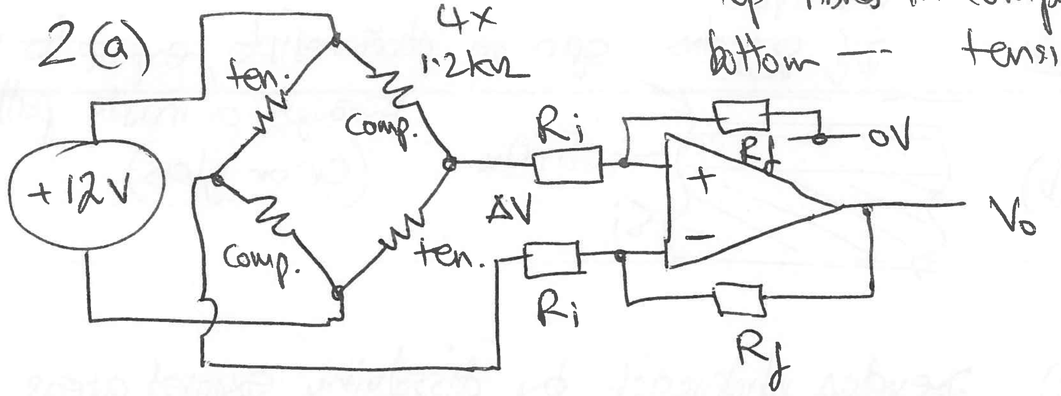
vs. 1·34 × 40·4 mV = 54·1 mV oil. (87% of water signal)

ie: rather similar signal levels, but pulse-echo time from water = 0·068 ms.

[20%]

2 (a)

top fibres in compression
bottom — tension

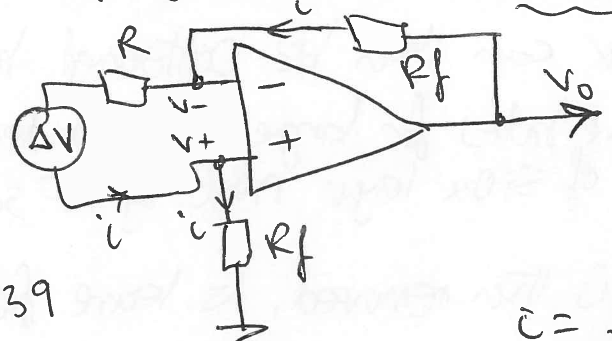


Connect fibre strain gauges in a bridge and input to a differential amplifier.

the ΔV signal for a full bridge $= \frac{\delta R}{R} \cdot V_s$

$\therefore$ at 0.2% strain: $\Delta V = \frac{2}{1000} \cdot 1.5 \cdot 12 = 36\,mV$

with a source impedance of 1.2kΩ for simplicity we can make $R_i = 0$ then $V_o = 2 \frac{R_f}{1.2k} \Delta V$)
(5) (0.036)



since: $V_- = V_+ = V$

$\frac{V_o - V}{R_f} = \frac{V}{R_f}$ $\therefore V_o = 2V$

$i = \frac{\Delta V}{R} = \frac{V}{R_f}$ $\therefore V_o = 2 \frac{R_f}{R} \Delta V$

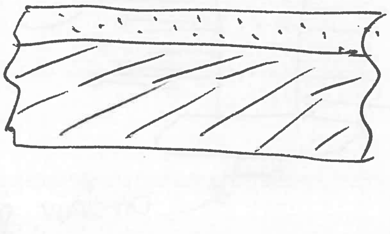
$G = \frac{5}{0.036} = 139$

So, choose $R_f = 83.3\,k\Omega$

[25%]

(b) (i) Surface micro-machining
- deposition of Si, SiO_xN_y
- photolithography
- wet chemical etching

(a)

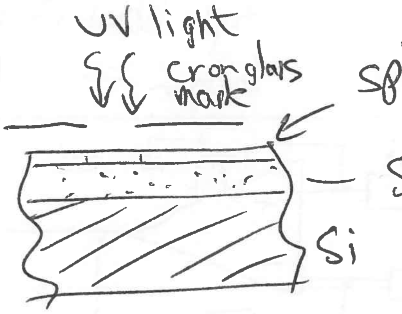


← deposit SiO_x from CVD

Si wafer

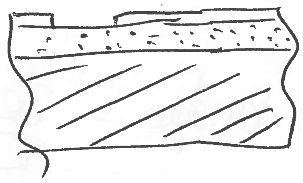
Silane + N_2O plasma

2(b) cont.



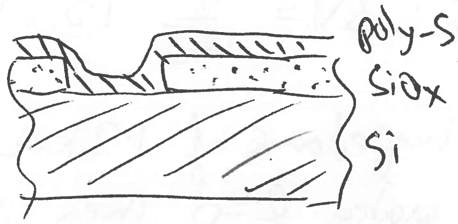
(b) spin on photoresist, expose to UV through a mask pattern (Cr on glass)

(c) Develop photoresist by dissolving exposed areas in caustic solution eg: NaOH



then etch in HF solution to dissolve SiOx or plasma etch in CF_4

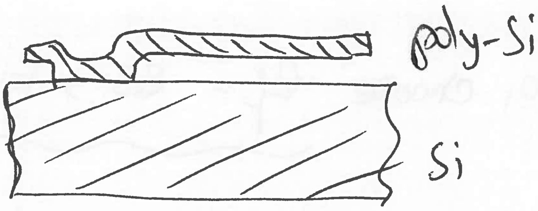
(d)



then deposit poly-Si from SiH_4 CVD heat/plasma deposition

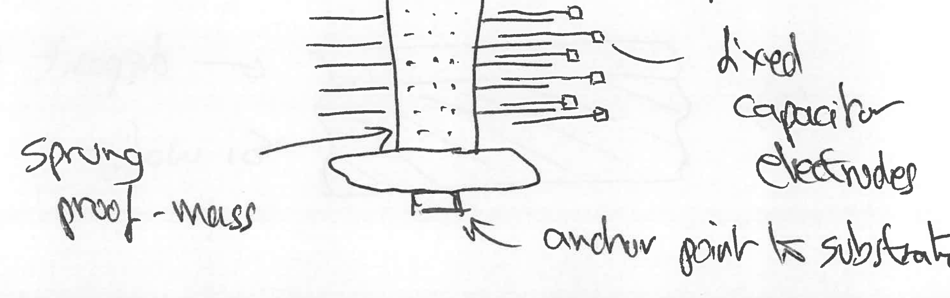
(e) Poly-Si layer can then be patterned by dry plasma etching (leave holes for large area under-etching) of SiOx layer next by HF solution

(f) SiOx layer is then removed, to leave free standing poly-Si structure



(g) can include Si Nitride insulation layers and metal layers (deposit by sputtering / evaporation).

(h) to form accelerometer



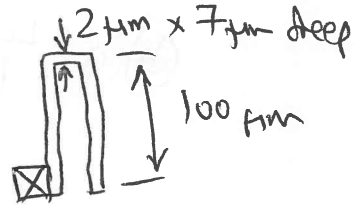
[20%]

2(b)(ii) Capacitor area $= 100 \times 100\times10^{-6} \times 7\times10^{-6} = 1.4\times10^{-7}\,m^2$

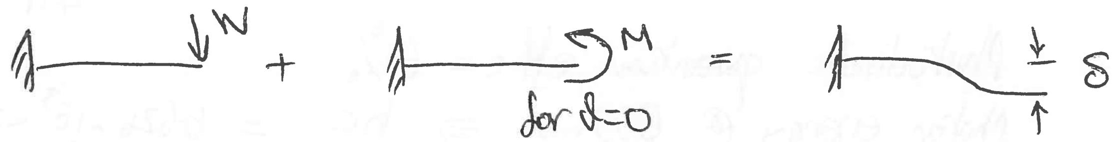
— " — gap $= 1.5\times10^{-6}$ m

$\therefore$ Total capacitance $= \dfrac{A\epsilon_0}{d} = \underline{0.413\ pF}$ [10%]

(iii) Each hairpin tether spring:



Beam ends do not change angle



$M = \dfrac{WL}{2}$ $\therefore\ \delta = \dfrac{WL^3}{3EI} - \dfrac{WL^3}{4EI} = \dfrac{WL^3}{12EI}$ Spring constant $k = W/\delta$

For a hairpin tether, there are 2 such beams, and 1 tether at each corner.

$E = 110\ GN\,m^{-2}$, $I = \dfrac{dw^3}{12}$

$\therefore\ k = \dfrac{12EI}{L^3} \times 4/2$ ($L = 100\times10^{-6}$ m)

$d = 7\times10^{-6}$ m

$w = 2\times10^{-6}$ m

$\therefore$ Spring constant, k for proof mass $= \underline{12.3\ Nm^{-1}}$ [20%]

(iv) Proof mass $\simeq 1.96\times10^{-9}$ kg

$\therefore$ Deflection @ $100\ ms^{-2} = \dfrac{100 \times 1.96\times10^{-9}}{12.3} = 1.59\times10^{-8}$ m

$\therefore$ % change in air gap and capacitance $= \dfrac{1.59\times10^{-8}}{1.5\times10^{-6}} \times 100 = \underline{1.06\%}$ [10%]

(v) $C = \dfrac{A\epsilon_0}{x}$, $E = \frac{1}{2}CV^2 = \frac{1}{2}\dfrac{A\epsilon_0 V^2}{x}$, $F = \dfrac{dE}{dx}$ (force)

$\therefore\ F = -\frac{1}{2}\dfrac{A\epsilon_0 V^2}{x^2} = -\frac{1}{2}\dfrac{CV^2}{x}$ or $V = \sqrt{\dfrac{2Fx}{C}}$

$\therefore\ V = \left(\dfrac{2\times100\times1.96\times10^{-9}\times1.5\times10^{-6}}{0.413\times0.60\times10^{-12}}\right)^{1/2} = \underline{1.54\ V}$ [15%]

Closed-loop response gives better linearity, dynamic range and transient response – electrical feedback increases k.

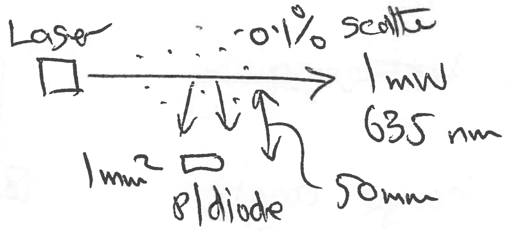
3 (a) $R = Ae^{\beta'/T}$

$1000 = Ae^{3200/(20+273)}$ $\therefore A = 0.0181$

$\therefore$ @ 60°C $R = 0.0181\, e^{3200/(60+273)} = 270\ \Omega$

[10%]

(b)(i)



optical scattered $\therefore$ power on p/diode $= 10^{-3} \times 10^{-3} \times \frac{1}{4\pi\, 50^2} = 31.8\ pW$

Photodiode quantum effic = 60%

photon energy @ 635nm $\Rightarrow \frac{hc}{\lambda} = \frac{6.626 \times 10^{-3} \times 3 \times 10^{8}}{635 \times 10^{-9}} = 3.13 \times 10^{-19}$

$\therefore$ photon flux detected $= \frac{31.8 \times 10^{-12}}{3.13 \times 10^{-19}} = 101.6 \times 10^{6}$ photon/sec

$\therefore$ photo current $= 1.6 \times 10^{-19} \times 101.6 \times 10^{6} \times 0.60 = 9.75\ pA$

[20%]

(ii) $10\, M\Omega\ //\ 10\, nF$ $\quad f_{-3dB} = \frac{1}{2\pi RC} = 1.59\ Hz$

Signal amplitude $= 10 \times 10^{6} \times 9.75 \times 10^{-12} = 97.5\ \mu V$

op amp noise $= 10 \times 10^{6} \times 1.2 \times 10^{-12} \times \sqrt{1.59} = 15.1\ \mu V_{rms}$

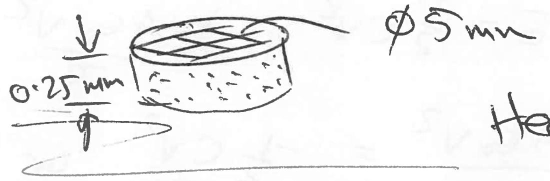
resistor thermal noise $= \sqrt{4kTRB} = 0.51\ \mu V_{rms}$

$V_{n\,total} = \sqrt{\Sigma v_n^2} = \sqrt{15.1^2 + 0.51^2} = 15.1\ \mu V_{rms}$

$\therefore$ S/N ratio $\simeq 6.5 : 1$

[25%]

(c) (i)



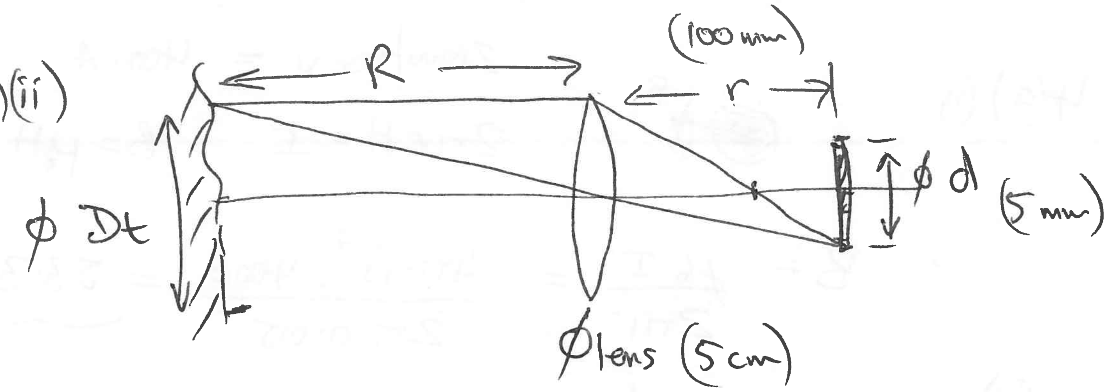
Heat flow $= \frac{kA\,\Delta T}{d} = P_h$

Thermal rating $= \frac{\Delta T}{P_h} = \frac{d}{kA} = \frac{0.25 \times 10^{-3} \times 4}{0.05 \times \pi (5 \times 10^{-3})^2}$

$= 255\ °C/W$

[10%]

3(c)(ii)



Lambert's Law, $\delta W = \frac{W \cos\theta}{\pi} A \, \delta\omega = \frac{W}{\pi} \cdot \frac{\pi D_t^2}{4} \cdot \frac{\pi \phi_{lens}^2}{4R^2}$

Now $\frac{D_t}{R} = \frac{d}{r}$ $\therefore$ $\delta W = \frac{W}{\pi} \cdot \frac{\pi^2}{16} \cdot \frac{d^2}{r^2} \cdot \phi_{lens}^2$

$\therefore \delta W = \epsilon \, \sigma_{SB} \, T^4 \, \frac{\pi}{16} \, \frac{d^2 \phi_{lens}^2}{r^2} = 8.15 \times 10^{-4} \, W$

($\sigma_{SB} = 5.67 \times 10^{-8}$, $\epsilon = 0.95$, $T = (60 + 273.2)$)

$\therefore$ temperature rise of detector $= 8.15 \times 10^{-4} \times 255 = 0.208\,^\circ C$

and with $P_s = 2.6 \times \frac{1.38 \times 10^{-23}}{1.6 \times 10^{-19}} \ln\left(\frac{2 \times 10^{-3}}{5.6 \times 10^{-6}}\right) = 1.32 \, mV/K$

$\therefore$ Signal $= 0.208 \times 1.32 = 0.274$ mV [20%]

(iii) Mass of detector $= \rho A d = 150 \cdot \frac{\pi}{4} (5 \times 10^{-3})^2 \cdot 0.25 \times 10^{-3}$

$= 7.36 \times 10^{-7}$ kg

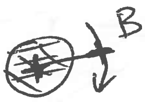
$\frac{kA T}{d} = m c_p \dot{T}$ for heat flux to detector, a 1st order

D.E. with exponential soln. $\tau = \frac{m c_p d}{kA} = 0.225$ secs.

So bandwidth $f \simeq \frac{1}{2\pi\tau} = 0.71$ Hz

[15%]

4(a) (i)



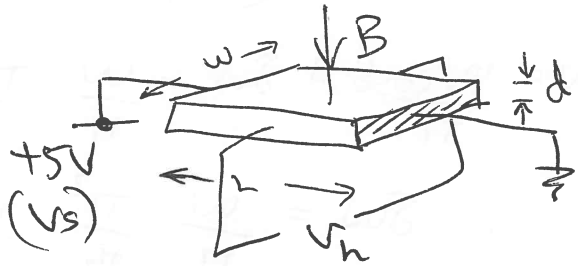
$2MW/500V = 4000A$

$2\pi r H = I \quad B = \mu_0 H$

$$\therefore B = \frac{\mu_0 I}{2\pi r} = \frac{4\pi \times 10^{-7} \cdot 4000}{2\pi\, 0.015} = 53.3\ mT$$

[15%]

(ii)



Force balance on electrons: $Bqv = qE$

$$\therefore B\frac{V_s}{L}\mu = \frac{V_h}{w}$$

$$\therefore V_h = B\mu\frac{w}{L}V_s = 0.8B$$

(μ = 0.16, V_s = 5)

$\therefore$ responsivity = 0.8 V/T

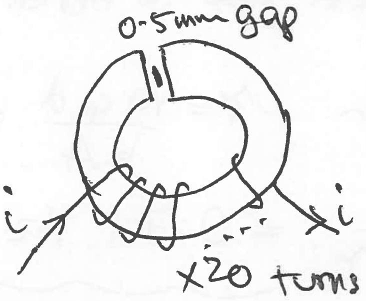
$\therefore$ signal = 42.6 mV @ 4000A

[20%]

(iii) To improve immunity to external influences, use another Hall sensor diametrically opposite and connect the signals differentially. As the cable produces a circular field the signals add but uniform external fields will cancel.

[10%]

(b) (i)



$\Sigma Hl = Ni$ and $B = \mu_0 H_a = \mu_0 \mu_r H_m$

$$H_a g + H_m l = Ni = H_a g + H_a \frac{l}{\mu_r}$$

$$\therefore B = \frac{Ni\mu_0}{(g + l/\mu_r)}, \quad \phi = BA$$

$$L = \frac{N\phi}{i} = N^2 \mu_0 A / (g + l/\mu_r) = 28.3\,\mu H$$ [15%]

4(b)(ii) With 0.5 A = 10 A turns

$$B = \frac{N i \mu_0}{(g + l/\mu_r)} = \frac{10 \cdot 4\pi \times 10^{-7}}{0.533 \times 10^{-3}} = 0.0236\ T$$

$\Rightarrow V_{signal} = 0.0236 \times 0.80 \Rightarrow$ 18.9 mV [15%]

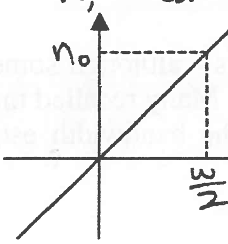
(iii) Resistance of Hall sensor $= \rho \frac{L}{A} = \frac{10^{-3} \cdot L}{15 \times 10^{-6} \cdot L} = 66.7\ \Omega$

Thermal noise $= \sqrt{4kTRB}$

So we need the bandwidth, B.

The response bandwidth may be estimated from considering the charge carrier transit time constant across the device, by diffusion. For simplicity, we shall assume a linear carrier concentration gradient.

n, excess carrier conc.



x, dist. across width from centre line

$n = \frac{2 n_0 x}{w}$ $\therefore \frac{dn}{dx} = \frac{2 n_0}{w}$

Fick's Law:– carrier flux $f = -D \frac{dn}{dx}$, $D = \frac{\mu k T}{q} = 4.14 \times 10^{-3}$

N = total excess carriers 1 side:

$$N = Ld \int_0^{w/2} \frac{2 n_0}{w} x\, dx = \frac{n_0 w L d}{4}$$

consider 1 side: $\frac{dN}{dt} = f L d = -D \frac{2 n_0}{w} L d = -D \frac{2 L d}{w} \frac{4N}{w L d}$

$\therefore \frac{dN}{dt} = -\frac{8DN}{w^2} \Rightarrow$ soln: $N = N_0 e^{-t/\tau}$ $\therefore \frac{-N_0}{\tau} e^{-t/\tau} = \frac{-8 D N_0 e^{-t/\tau}}{w^2}$

$\therefore$ time constant $\tau = \frac{w^2}{8D}$ so, $t_{rise} = 2.2\tau$ and $f_{-3dB} = \frac{1}{2\pi\tau}$

$$\therefore \tau = \frac{(250 \times 10^{-6})^2}{8 \times 4.14 \times 10^{-3}} = 1.89\ \mu s \quad \therefore f_{-3dB} = B = 84.3\ kHz$$

Thermal noise $= 0.31\ \mu V_{rms} \cong 0.38\ \mu T \cong 8.2\ \mu A$ equiv. current

[25%]

Q1 Ultrasonic level sensing

A popular question which was well answered by most. Most candidates made a good attempt at calculating the signal levels, which were quite complex in the latter stages with multiple media and some did not take correct account of the beam angle. The pulse-echo transit times were nearly always correct however.

Q2 MEMS fabrication, device capacitance & strain gauges

A quite well-answered question on MEMs fabrication (surface micro-machining), with most candidates knowing the main steps, however process details were often missing. The estimate of device capacitance often only included one side, although the sensing voltage feedback was generally quite well understood. The first part on strain gauge amplification attracted a variety of feasible circuits.

Q3 Optical smoke detector and pyrometer system

A very popular question, which was well answered in most cases and with a few model answers. Noise levels were generally well estimated using the amplifier bandwidth determined by the feedback RC network. The pyrometer analysis was generally correctly done, including the first part on detector thermal rating, although the algebra sometimes went awry.

Q4 Hall effect current sensors

This was a popular question, which attracted some high quality attempts - although some candidates failed to calculate the flux density and Hall sensor responsivity correctly. Many recalled the Hall effect sensor equations – or at least remembered the end result to use for the bandwidth estimate. The inductance calculation was not correct in a number of cases though.