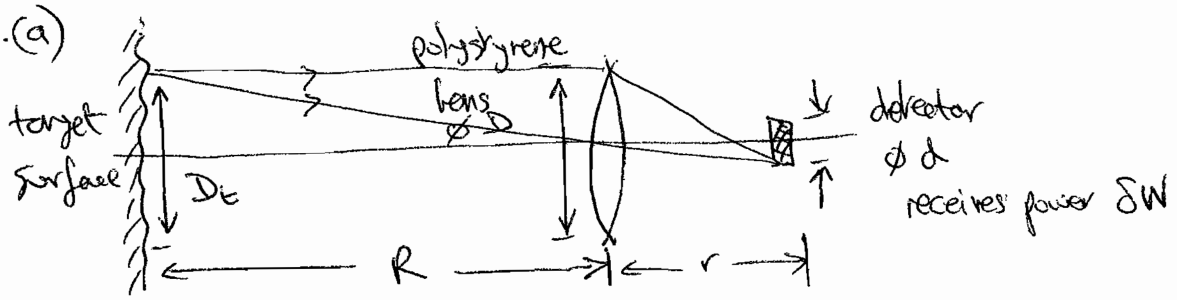
2009 PART IIB 4B13 ELECTRONIC SENSORS AND INSTRUMENTATION

Dr P A Robertson

1.(a)



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

Stephan's Law $W = \epsilon\,\sigma_{SB}\,T^4$

$\therefore$ with $\frac{D_t}{R} = \frac{d}{r}$ similar triangles

then $\delta W = \epsilon\,\sigma_{SB}\,T^4\,\frac{\pi}{16}\,\frac{d^2 D^2}{r^2}$ with $\epsilon = 0.95$

$T = (273+15)\,K$

$\sigma_{SB} = 5.6\times10^{-8}\ W/m^2K^4$

$D = 0.05\,m$

$d = 0.005\,m$

$\therefore\ \delta W = 4.49\times10^{-4}\ W$

$r = 0.1\,m$

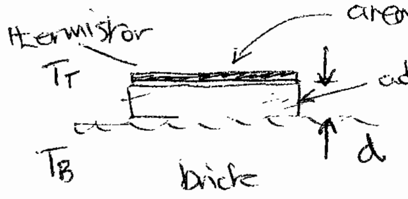
$\therefore$ temperature rise of detector $= 200\times 4.49\times10^{-4} = \underline{0.09}\ {}^\circ C$ (or K)

Hence, detector signal $= 0.09\times P_s \Rightarrow \underline{1.07\times10^{-4}\ V}$

$\left(\text{where } P_s = \frac{2.6\times1.38\times10^{-23}}{1.6\times10^{-19}}\times\ln\left(\frac{10^{-3}}{5\times10^{-6}}\right) = 1.19\times10^{-3}\ V/K\right)$

[40%]

(b) Power dissipation in resistor $= I^2R = 0.01^2\cdot100 = 0.01\,W = P$



$\therefore P$, Heat flux $= \frac{\underset{\text{thermal conduct.}}{k}\,\overset{\text{area}}{A}\,\overset{\Delta T}{(T_T - T_B)}}{\underset{\text{adhesive thickness}}{d}}$

1(b) cont'd.

Assuming steady state and thermal mass of brick is infinite : $0{\cdot}01 = \frac{0{\cdot}35 \; . \; 10\times10^{-6} . \; \Delta T}{0{\cdot}2\times10^{-3}}$

∴ ΔT (temp error) $= 0{\cdot}57\,^{\circ}C$ (ork) [25%]

(c) Firstly, calculate thermal power received by detector from new target, $\delta W' = 4{\cdot}49\times10^{-4} \times \left(\frac{0{\cdot}85}{0{\cdot}95}\right) \times \left(\frac{273+25}{273+15}\right)^4$

∴ $\delta W' = 4{\cdot}61\times10^{-4}$ W (increase of 2·6%)

For the thermistor $R_t = Ae^{\beta'/T}$ with $R_t = 1000$ @ $T = 293K$

$\beta' = 3500$

∴ $A = 6{\cdot}49\times10^{-3}$

[So, at 10°C $R_t = 1525\,\Omega$ (ambient 283K)]

and with $\delta W'$ incident on detector, $T = 4{\cdot}61\times10^{-4}\times200 + 283$ K

$= 283{\cdot}0922K$

∴ $R_t' = 1519{\cdot}25\,\Omega$

with δW incident on detector $T = 4{\cdot}49\times10^{-4}\times200 + 283K$

$= 0{\cdot}0898K + 283K$

∴ $\Delta T = 2{\cdot}4\times10^{-3}$ K

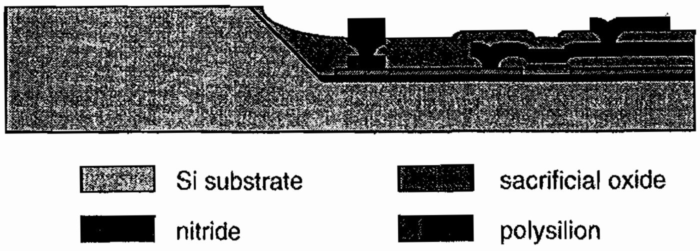
and $R_t = 1519{\cdot}41\,\Omega$ ∴ $\Delta R = 0{\cdot}16\,\Omega$ drop

[35%]

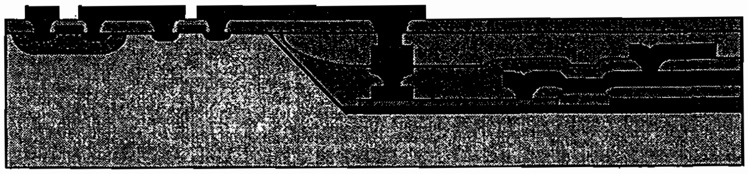
1 (a) There are several methods to integrate MEMS with CMOS – (i) MEMS-first / CMOS-last (ii) CMOS-first, MEMS-last and (iii) interleave the two processes.

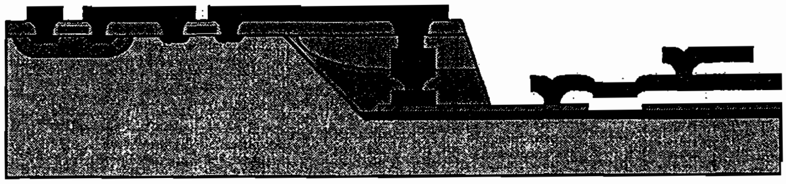
In a MEMS-first process, it is necessary to planarise the processed wafer before it is sent to a CMOS foundry; otherwise the topography become unacceptable for further CMOS processing. In this route it is also essential to ensure that the materials utilised for MEMS processing are acceptable for IC processing. In a CMOS-first, MEMS-last process, there may be a restriction with the processing temperatures at which common MEMS structural thin films (e.g. polysilicon) are deposited. These may be incompatible with the temperatures withstood by metallisation (e.g. aluminium) or inter-metal dielectrics used in CMOS processing. Interleaving the two processes is possible, but complex, as it is necessary to optimise for both the electronic and mechanical functionality of materials involved in the process. Non-standard MEMS processes also affect the overall yield of integrated processes reducing the cost benefits of batch fabrication.

An example of a MEMS-first process is the Sandia integrated MEMS process. Here the MEMS is fabricated in a KOH-etched well in a starting silicon substrate. Two levels of structural polysilicon and sacrificial silicon dioxide are deposited and patterned in this well as shown in cross-section below:



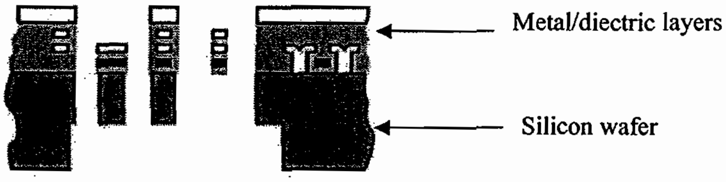
Next, a planarisation process is followed to planarise the well and perform the CMOS processing as shown in cross-section below. The top-level metal can be utilised as an interconnect between the MEMS and the CMOS. Finally, the CMOS region is protected (by photoresist) while a buffered hydrofluoric acid etch is used to remove the silicon dioxide sacrificial layers, thereby freeing up the MEMS structures for mechanical functionality.





[30%]

2 (b) In CMOS micromachining, the CMOS process is carried out first at a standard IC processing facility to process the integrated circuits. The MEMS elements are then built out of the processed CMOS wafer by utilising the metal/dielectric stack as a structural layer or even micromachining the silicon substrate itself to construct the MEMS device. However, there is limited control on the structural properties of the thin-films fabricated as part of the composite MEMS structure. This process is particularly suitable when the integration with electronics is more important than the requirement for the control of the material properties of the MEMS structure. A representative cross-section is as shown below:



[20%]

(c) Thermo-mechanical noise is the noise associated with the Brownian motion of the proof mass of an accelerometer. This arises because the proof mass is in thermal equilibrium with its environment and hence vibrates due to the thermal energy that it possesses at room temperature and due to its interactions with fluctuations in gas pressure in the ambient due to random thermal motions of individual atoms in the gas and the interaction of this motion with that of the proof mass. The resultant random vibration of the accelerometer proof mass results in a noisy accelerometer output that sets its fundamental resolution (assuming electronic noise is not dominant).

[20%]

(d) $C = N\frac{\varepsilon_0 A}{g} = \frac{200 \times 8.85 \times 10^{-18} \times 6 \times 400}{1}$ =4.25 pF

The voltage required for force feedback can be calculated as:

Capacitance for force feedback = 2.12 pF

A force balance is achieved when the electrostatic force balances the inertial force:

$\frac{1}{2g}CV^2 = ma \Rightarrow V = \sqrt{\frac{2mag}{C}} = \sqrt{\frac{2 * 10^{-9} * 50 * 10^{-6}}{2.12 * 10^{-12}}}$ = 217 mV which gives the required force-feedback voltage.

[30%]

3(a) Measurement (sometimes Random) Uncertainty comes from repeated measurements that are taken when any Calibration is done. The Mean of these Values is the best estimate of the measured quantity, and the Standard Deviation (σ_{n-1}) gives an indication of their scatter; as usual

Std · Dev $= \left(\frac{1}{n-1}\sum(x_i - \text{Mean})^2\right)^{1/2}$ where x_i is each reading and n readings taken.

Now $U_m = \text{Std Dev}/n^{1/2}$ = Standard Measurement Uncertainty.

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To make use of the mean value of the measurement, corrections have to be done depending on past calibrations of the instrument and depending on any temperature differences between the present laboratory and the calibration laboratory. Each of these corrections will have a stated uncertainty and it is the combination of these that gives the

System Uncertainty, $U_s = \left(\left(\frac{U_{cal}}{2}\right)^2 + U_w^2 + U_T^2 + \cdots\right)^{1/2}$

where U_{cal} is the uncertainty at Calibration (expanded)
U_w is due to wiring emfs or resistances.
U_T is due to temp differences × temp coeff of instrument.

(Note will have to be taken if any of these errors do not have gaussian distributions but are rectangular shown as errors having limits, say as ±5°C for temp changes).

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Lastly U_m and U_s are combined but with a ×2 multiplier to allow a 95% confidence that the errors are not exceeded, thus

Total Expanded Uncertainty $= 2 \times (U_m^2 + U_s^2)^{1/2}$.

[30%]

3(b) When one of a group instruments has to be selected to go for calibration, then before calibration

ⓐ Intercompare all similar instruments regularly and decide which is "best", having the least temperature coefficient, is least affected vibration and being moved and, if battery maintained while away from mains power, has a good new battery for power while travelling

ⓑ Note the differences between the "best" instrument and all the others by using a check standard to measure, carefully on the day before despatch.

ⓒ On return of the calibrated instrument, carefully repeat step ⓑ to see if the differences are the same. If so, then the effect of travel has had no effect. (If not, repeat calibration)

ⓓ Now from the calibration certificate, use the differences to attribute new values to all the instruments in the group.

[30%]

—— 11 ——

3(c) Using the data given:-

Temp °C	Mean of A&B (Ω)	So meter reads	Corrected values for X	change/5°	Corrected values for Y	change/5°
10	1000.4	0.7Ω low	990.0	17.2Ω	1020.0	16.7Ω
15	1001.7	0.6Ω hi	1007.2	17.2	1036.7	17.3
20	1000.7	0.4Ω low	1024.4	17.2	1054.0	18.1
25	1001.6	0.5Ω high	1041.6	17.2Ω	1072.1	18.7Ω
30	1001.1	Correct	1058.8		1090.8	

So for sensor X, change is 17.2Ω / 5°C

$$\text{or } \frac{17.2}{1000 \times 5} = 0.344\,\%/°C$$

As the 4 change steps give the same coefficient, the uncertainty is very low and could be defined by the resolution of the ohmmeter of ±0.1Ω or $\frac{0.1}{1000 \times 5}$ = 0.004 %/°C. But an uncertainty estimate of ±0.008 %/°C would be quoted including a coverage factor of 2 for 95% confidence

Contd

3(c) contd.

For the sensor Y, the resistance changes rise steadily as the temperature rises so it is NOT LINEAR. It has a mean value of 17.7Ω / 5° change and it is close to that of X. But uncertainty estimates from the std dev are meaningless

The corrections for the Ohmmeter are −0.7, +0.6, −0.4, +0.5, 0 so giving a mean of zero and $\sigma_{n-1} = 0.56\Omega$ on a calculator. 4 readings give

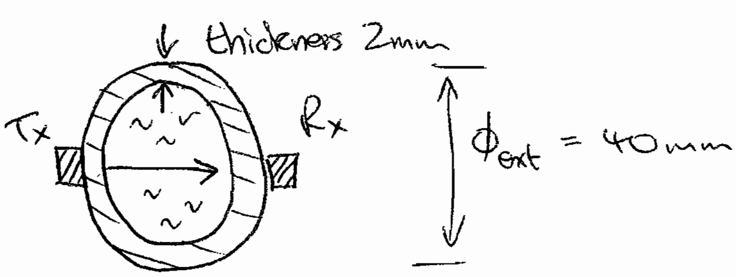
$$\text{Standard Uncertainty} = \frac{0.56}{\sqrt{4}.1000} = 0.028\%$$

or approx 0.06% expanded

Uncertainty using the X2 coverage factor for a confidence of about 95%

[40%]

4(a)



Transit time = Σ distances/speed of sound

$$t = \frac{2\times10^{-3}}{6000} + \frac{36\times10^{-3}}{1500} + \frac{2\times10^{-3}}{6000} = \underline{2.47\times10^{-5}\,s}$$

Cu H2O Cu

Pulse transit around pipe (½ way) = $\frac{38\times10^{-3}\times\pi}{2} \Big/ 6000 = \underline{9.95\times10^{-6}\,s}$

[15%]

(b) Power in PZT transducer $= \frac{V^2}{R} = \frac{144}{100} = 1.44\,W$

Conversion to u/sonic = ×10% = 0.144 W

u/s Coupling coeff. $P_t = \frac{4Z_1Z_2}{(Z_1+Z_2)^2}$, $Z = \rho \times v$

$$\begin{tikzcd}
Z_{PZT} = 30\times10^6\ kg\,m^{-2}s^{-1} \arrow[dr] & & \\
Z_{Cu} = 53.4\ \text{"} \arrow[r] \arrow[ur] \arrow[dr] & 0.92 & \\
Z_{limescale} = 1.2\ \text{"} \arrow[r] & 0.086 \arrow[r] & 0.106 \\
Z_{water} = 1.5\ \text{"} \arrow[ur] & 0.99 \arrow[ur] &
\end{tikzcd}$$

P_t: 0.92, 0.086, 0.99 → 0.106

Attenuation factor $= \times 10^{-\frac{dB/m \times m}{10}}$ ⇒

4mm copper	0.993
10mm limescale	0.891
36mm water	0.898
26mm water	0.925

(i) Rx power $= 0.144 \times 0.92^2 \times 0.106^2 \times 0.993 \times 0.898 =$ 1.22 mW

Rx elect. power $= 0.1 \times 1.22\times10^{-3} = \frac{V^2}{100}$ ∴ V = 0.110 V loaded 100Ω

or 0.220V open cct.

4(b)(ii)

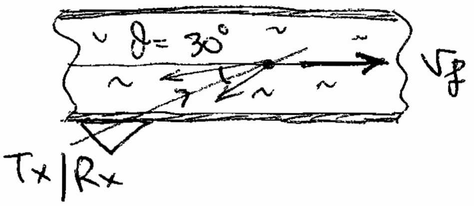
$$Rx\ \text{power} = 0{\cdot}144 \times 0{\cdot}92^2 \times 0{\cdot}086 \times 0{\cdot}99^2 \times 0{\cdot}993 \times 0{\cdot}891 \times 0{\cdot}925$$
$$= 7{\cdot}23 \times 10^{-4}\,W$$

$$\therefore Rx\ \text{electrical} \not> 0{\cdot}1 \times 7{\cdot}23 \times 10^{-4} = \frac{V^2}{100}$$

$\therefore V = 0{\cdot}085\,V$ loaded
or $0{\cdot}17\,V$ o/cct.

[50%]

(c)



V_s = speed of sound in liquid
V_f = flow velocity

Consider particle or bubble in fluid causing back-scattered u/sonic signal where component of fluid velocity resolved in direction of u/sonic beam $= V_f \cos\theta$

For each $\lambda/2$ distance moved along u/sonic beam axis, 1 beat frequency cycle is seen in the Rx signal.

$$\therefore f_{Dopp.} = \frac{V_f \cos\theta}{\lambda/2} \qquad \text{where } \lambda = \frac{V_s}{f_{u/s}}$$

$$\therefore f_{Dopp} = 2\,\frac{f_{u/s}\, V_f \cos\theta}{V_s}$$

So, with 5mm of limescale, internal dia. = 26mm

$$\therefore V_f = \frac{\dot{v} \times 10^{-3}}{\pi (26 \times 10^{-3})^2/4} = \dot{v}\ 1{\cdot}883$$

$\dot{v}$ = flow rate litres/sec

[25%]

$$\therefore f_{Dopp} = \frac{2 . f_{u/s} . \dot{v} . 1{\cdot}883 . \cos 30^\circ}{1500} = 2174\ Hz / \text{litre/sec}$$

(d) Some bubbles are required to give a back-scatter however too many result in signal attenuation, noise and poor coupling of the u/sonic energy as the acoustic impedance falls. Also, flow rate of the 2-phase flow becomes meaningless based on volume flow; derived from velocity.

[10%]

5(a) The Hall effect magnetic sensor operates by moving charge carriers being deflected by a magnetic field. A slice of semiconductor is arranged to have a current passing along one axis (hence moving carriers). If a magnetic field is present in an axis orthogonal to the current flow, then the charge carriers are deflected along the remaining third axis. The carriers are thus deflected until an equilibrium condition results where the force on the carriers due to the electrostatic field produced from carrier accumulation (repelling their deflection) cancels the magnetic force Thus the semiconductor slice produces a 'Hall voltage' across 2 faces, proportional to the applied magnetic field and current.

A fluxgate sensor employs the periodic, alternating saturation of a high permeability core inside a solenoid coil driven by an a.c. current. The same, or another, coil has a voltage induced in it proportional to the rate of change of magnetic flux within the core. If an external magnetic field also couples with the core then the saturation in one direction is delayed and conversely, advanced in the opposite direction. Thus an asymmetry in the induced voltage positive and negative peaks occurs due to the external field. This is equivalent to even harmonics being present in the voltage waveform - especially the 2nd harmonic. If 2 cores driven in anti-phase couple to a single pick-up coil then the fundamental and odd harmonics cancel with even (2nd) harmonics adding to give a clearer signal

[25%]

(b) Demagnetising factor $D = \frac{1}{\mu_{eff}} = 30^{-2}(\ln 60 - 1) = 3.44 \times 10^{-3}$

$\therefore \mu_{eff} = 291$

Hence, flux density in core = $\mu_{eff} B_{ext}$ and voltage induced in pick-up coil $= 2\pi f_g \, \mu_{eff} B_{ext} A N$ @ $2f_g$

$A = \pi d^2/4$

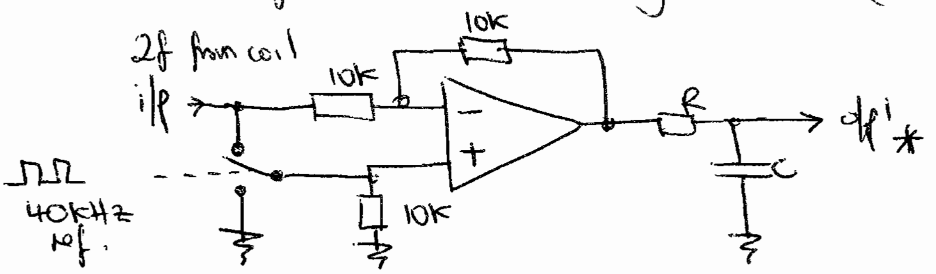
$f_g = 20\text{kHz}$

So, with 400 coil turns :

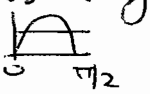
$V_{i_{2f}} = 2\pi . 20\times10^{3} . 291 \, \frac{\pi}{4} 10^{-6} . 400 \, B_{ext} = 11488 \, B_{ext}$.

5(b) cont'd.

We wish to demodulate the 40kHz (2f) signal to produce a d.c. voltage. Use a switching inverter (PSD)



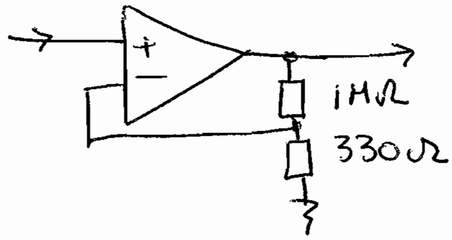
choose RC roll-off
eg: 100Hz
$R = 10k\Omega$
$\omega_0 = \frac{1}{2\pi RC}$
$\therefore C = 160\,nF$

when set for in-phase switching, the PSD has a gain of the average of a sine wave over ½ cycle  $= \frac{2}{\pi}$

Hence, output signal $= \underset{0.1\%}{10^{-3}} . \underset{B_{earth}}{45\times10^{-6}} . \underset{\text{fluxgate sens.}}{11488} . \underset{\text{demod.}}{\frac{2}{\pi}} = 0.33\,mV$

Hence, a gain of $\frac{1}{0.33\times10^{-3}} \approx 3{,}000$ is required.

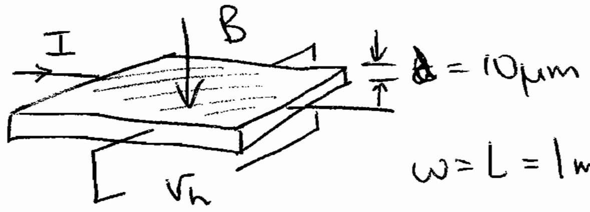
* o/p'

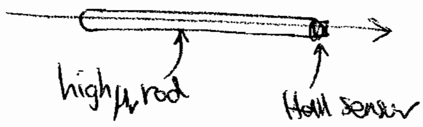


final o/p. ≃ 1V for passing car.

[35%]

(c)





$F = Bq\,v_d$ (magnetic), $I = nAv_d q = \frac{VA}{\rho L}$
$= qE$ (electrostatic)

$\therefore B\cancel{q}v_d = \cancel{q}E = \cancel{q}\frac{V_h}{w}$ force balance, where $v_d = \frac{V}{L}.\mu$ (drift velocity, mobility)

$\therefore \frac{BV}{L}\mu w = V_h = 10^{-3}.45\times10^{-6}.291.5.0.14 = 9.2\,\mu V$
(≡204 V/T)

[30%]

(d) $v_n = \sqrt{4kTRB}$ $R = \frac{\rho L}{\cancel{A}\,w\times d} = \frac{0.045}{10\times10^{-6}} = 4500\,\Omega$

$\therefore v_n = 85\,nV_{rms}$ ≡ 0.42nT with core, or 0.12μT without

[10%]