2008 IIB 4B13 ELECTRONIC SENSORS AND INSTRUMENTATION DR PA ROBERTSON

413 CRIB 2008

1 a) $R = R_0 e^{\beta'/T}$ (β' = 3000; T = temptr. in K)

$f = \frac{1}{CR}$ ($C = 100\times10^{-9}$)

$R^{(293K)}_{20°C} = 1000 \therefore R_0 = 0.0358\ \Omega$

$R^{(232)}_{50} = 386 \therefore f = 25.91$ kHz

$R^{(373)}_{100} = 111 \therefore f = 90.09$ kHz

$\therefore \Delta f = 64.2$ kHz

b) $f = \frac{1}{CR_0 e^{\beta'/T}} = \frac{1}{CR_0} e^{-\beta'/T}$

$\therefore \frac{df}{dT} = \frac{\beta'}{T^2} e^{-\beta'/T} \cdot \frac{1}{CR_0} = 8.032\times10^{6} \cdot e^{-\frac{3000}{323}} = 743$

@ T = 323 K (50°C)

$\therefore \left.\frac{df}{dT}\right|^{323K}_{50°C} = 743$ Hz/°C

Hence 50→80°C ⇒ +22.3 kHz = 48.2 kHz (25.9 kHz)

assuming linear.

But, actually we get 48.2 kHz with $f = \frac{1}{CR} \therefore R = 231\Omega$

with $C = 10^{-7}F$

Hence $R = 0.0358\, e^{\frac{3000}{T}}$ and T = 342K = 69°C actual temp.

[whereas μP reads 80°C ∴ over-reads by 11°C]

c) Heat flux, $F = \frac{\text{thermal cond.}(k) \times \text{area}(A) \times \Delta\text{Temp.}(\Delta T)}{\text{thickness }(d)}$

$= \text{mass }(m) \times \text{specific heat cap.}(c_p) \times dT/dt\ (\dot{T})$

$\therefore \dot{T} = \frac{kA(T_\infty - T)}{m c_p d}$

putting $\tau = \frac{mc_pd}{kA}$ and $T' = \frac{(T - T_\infty)}{\tau}$

1 c) cont'd $$T' = -\gamma \frac{dT'}{dt}$$ 1st order D.E.

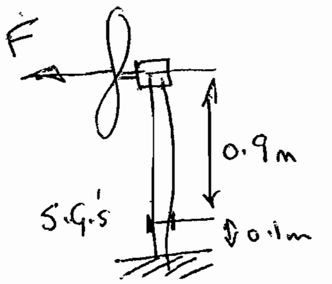
This has an exponential soln. $T' = X e^{-t/\gamma}$

$$T - T_\infty = \gamma X e^{-t/\gamma}$$ where $T = T_0$ @ $t=0$, $T = T_\infty$ @ $t=\infty$

$$\therefore \quad T = (T_0 - T_\infty) e^{-t/\gamma} + T_\infty$$

the risetime $\simeq 2.2\gamma = \dfrac{2.2 \cdot 0.1\times10^{-3} \cdot 1.2\times10^{3} \cdot 0.25\times10^{-3}}{0.35 \cdot 0.5\times10^{-4}}$

$$\Rightarrow \quad t_{10-90\%} = 3.77 \text{ secs.}$$

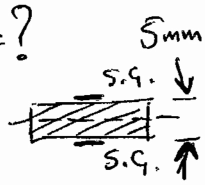
d) 

G.F. = 2 for metal S/G's

o/put from full bridge S.G.

$$o/p = \frac{\delta R}{R} \cdot 5 = 10\epsilon$$

I for rod $= \dfrac{1}{12} bd^3$ with $d = 5\times10^{-3}$ m $b = ?$



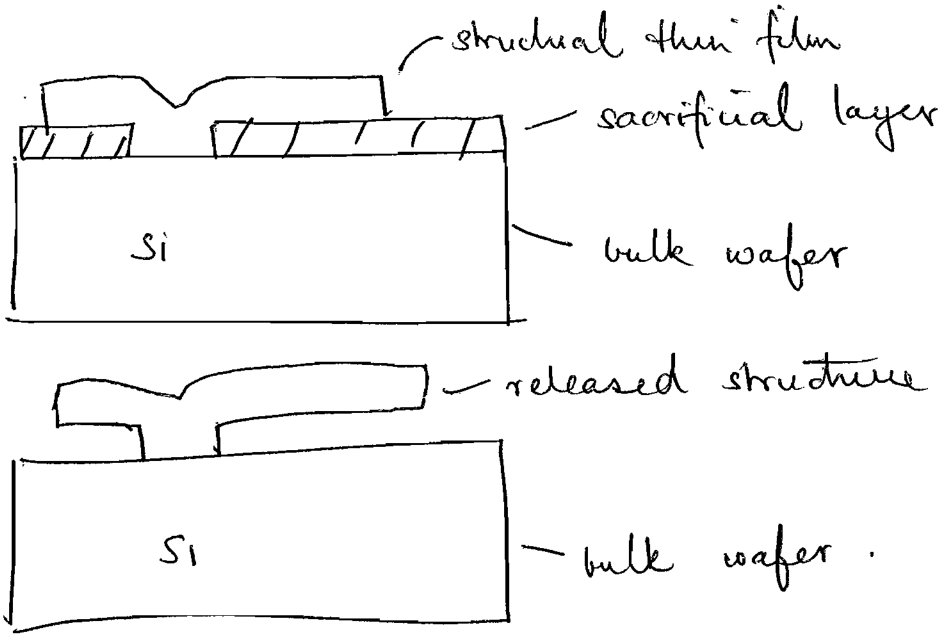
for steel, Young's Mod. $= 196\times10^9$ N/m^2

$$\frac{\sigma}{y} = \frac{M}{I} = \frac{\epsilon E}{y}$$ where $y = \dfrac{d}{2} = 2.5\times10^{-3}$

$$M = 0.9F = 0.9 \times 9.81 \times \text{Kgf}$$

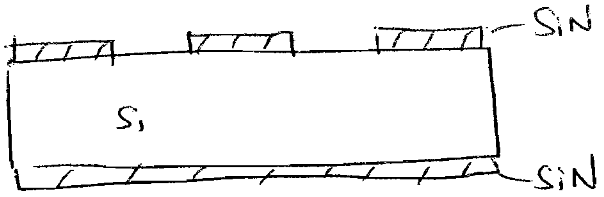
$$\therefore o/p = 10\times10^{-3} = \frac{0.9 \cdot 9.81 \cdot 2.5\times10^{-3} \cdot 10}{196\times10^{9} \cdot \frac{(5\times10^{-3})^3}{12} \cdot b}$$ $\therefore b = 10.8$ mm

Q2 a). In surface micromachining, micromechanical structures are built on the surface of a substrate (typically a silicon wafer) which itself is not patterned. The MEMS structures are composed of deposited and patterned thin films that are released at the end of the process by etching away a sacrificial layer.

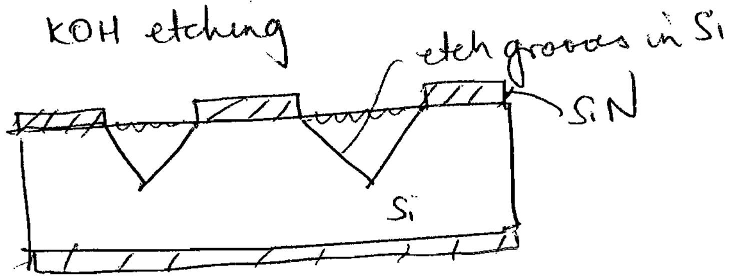


In bulk micromachining, the structures are fabricated into the wafer (substrate) thickness. A combination of wet and dry etching techniques may be used to define the device features in the ~~de~~bulk wafer.

2a) cont.



After KOH etching



Monolithic integration of MEMS with CMOS is particularly desirable when the close integration of circuits with MEMS devices enables the detection of small displacements (and resulting currents) with high signal-to-noise by reducing parasitic elements (eg. stray capacitance to ground at the interface between MEMS and CMOS electronics.

(b) Capacitive sensing can be implemented to provide better signal-to-noise and lower power as compared to piezoresistive sensing. In addition it is intrinsically less sensitive to temperature excursions. as compared to piezoresistive sensing. However, piezoresistive sensing is easier to implement in a bulk micromaching process which is best adapted for pressure sensors.

2(c) In open-loop mode, the capacitive MEMS accelerometer proof mass is allowed to respond to input acceleration and the resulting displacement is measured directly for e.g. using a set of differential sensing electrodes. In force-feedback mode, a voltage is applied using an alternate set of electrodes to maintain the nominal position of the proof mass (for 0 input acceleration) i.e. rebalance the proof mass output. The rebalance force provides an estimate of input acceleration. The force-feedback mode is more complex to implement but the linearity of the sensor could be extended using this technique.

(d) (i) Total $C = 100 \times 8.85 \times 10^{-12} \times \frac{500 \times 6 \times 10^{-6}}{1} \times 2$

$= 5.31\,pF$

(ii) $\frac{\Delta C}{C} \simeq \frac{x}{g} \simeq \frac{ma}{k} \times \frac{1}{g} \simeq \frac{10}{1} \times \frac{1 \times 10^{-9}}{10} \times \frac{1}{10^{-6}}$

$\simeq 10^{-3}$

3 a) Using a calculator, the 8 readings have a mean of 1·0075 V and a standard deviation of 1.13×10^{-3} (σ_{n-1})

Now this is developed across $1000 // 10^6$ or 999.001Ω.

So Sensor current is $V/R = \frac{1.0075}{999} = 1.0085$ mA

Standard Uncertainty is $\frac{\text{Std dev}}{\sqrt{\text{no of measurements}}} = 0.4 \times 10^{-3}$ or ·04%.

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b) Corrections :

ⓐ Due to 3 year interval since DVM last calibrated : it will now indicate 0·05 + 3 × 0·01 = ·08% higher than correct

So corrected sensor current is 1·0077 mA

ⓑ. Due to errors in 1000Ω resistor, it is now 0·06% above 1000,

So corrected sensor current $(\propto V/R)$ is 1·0071 mA.

(c) No correction due temp coeff

So corrected sensor current is 1·0071 mA

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c) Uncertainty budget :–

Due to :	Value %	Prob	Divisor	Std Unc %	$10^4 u^2$
Readings				·04	16
DVM Cal	3 yrs × 0·02 = ·06	Expanded	2	·03	9
Resistor Cal	4 × ·02 = ·08	"	2	·04	16
TC of DVM	±5 × ·02 = ·10	Rect	$\sqrt{3}$	0·058	33·3
TC of Resistor	±5 × ·01 = ·05	Rect	$\sqrt{3}$	·029	16·7

$\sqrt{\Sigma U^2} = \cdot 084$

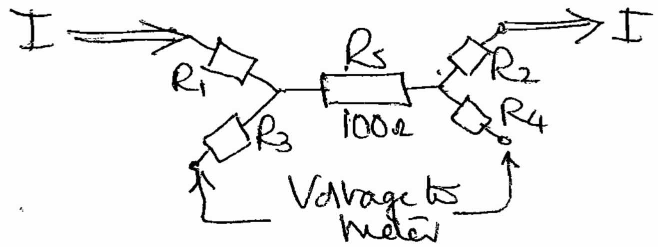
With ×2 multiplier,

Uncertainty of measurements is ± 0·17% or ± ·0017 mA on the indicated value of 1·0071 mA (given with a 95% confidence level).

(contd)

3c) cont. The bigger uncertainty contribution comes from the temp coeff of the DVM. If that could be reduced by a factor of 2 by selecting a better meter, then all the separate contributions are of the same order (summing the squares of contributions makes it override other effects at present).

3d) In a 100Ω sensor resistor the few mΩ in leads and terminal tightness may be important in a 2 lead device. However with a 4 terminal device it can be shown as :-

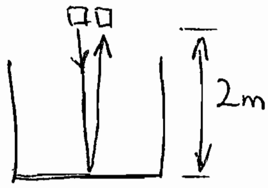


R_1 and R_2 (typically a few mΩ) model the terminal and lead resistance in package, but effect negligible as ONLY voltage across R_s is measured.

R_3 and R_4 model the lead and terminal resistance of the sensing circuit again a few mΩ. If the meter is high resistance so drawing very small currents of order μA, then effect is negligible

However it is still important that meter resistance is many times R_s — or its effect must be calculated.
The power dissipated in R_s increases its temperature and is usually limited to 10 mW if possible, otherwise another error is possible.

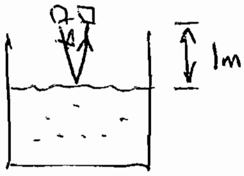
4 a)



$t = \dfrac{4\,m}{340\,m/s} = 0.0118\ s$

atten $= -4dB = \times 0.40$

b)



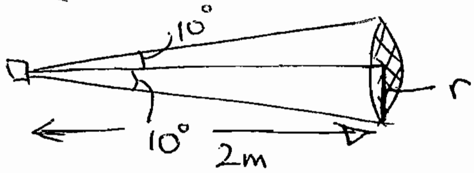
atten. over 2m $= -2dB = \times 0.631$

$Z_a = 340$ (1×340)

$Z_p = 1.15 \times 10^6$ (850×1350)

∴ pulse reflection coeff. $= \left(\dfrac{Z_a - Z_p}{Z_a + Z_p}\right)^2 \approx 1$

Beam divergence over 2m



$r = 2 \sin 10° = 0.347\,m = 347\,mm$

∴ area fraction of reflected beam captured by 2cm ϕ sensor

$= \left(\dfrac{20/2}{347}\right)^2 = 8.31 \times 10^{-4}$

$P_{trans} = 0.15 \cdot \dfrac{12^2}{5000} = 4.32\ mW$

$Z_{trans} = 10\, Z_a$

propn. of Coupled to air $= 1 - \left(\dfrac{10-1}{10+1}\right)^2 = \times 0.33 \Rightarrow 1.43\,mW$

Atten. over 2m $= \times 0.631 \Rightarrow 0.90\,mW$

Reflection prop. $= \times 1 \Rightarrow 0.90\,mW$

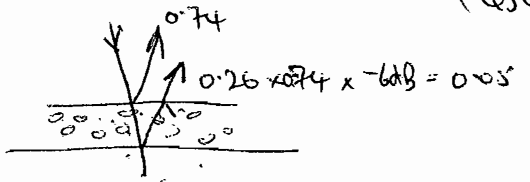
Area collection factor $= \times 8.31 \times 10^{-4} \Rightarrow 748\,\mu W$

Coupled back to trans $= \times 0.33 \Rightarrow 247\,\mu W$

Converted to electrical $= \times 0.15 \Rightarrow 37\,\mu W = \dfrac{V_r^2}{5000}$

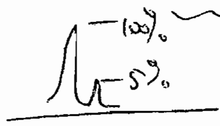
$\therefore V_r = 0.43\,V$

4c) Foam reflection coeff $= \left(\frac{4500-340}{4500+340}\right)^2 = 0{\cdot}74$



$\therefore$ 26% signal lost

Also we will ge 2 received peaks



- the second is smaller than first.

The sensor will under-read the time due to the foam thickness of 5 cm ie: $t_{echo} = -5\%$, but then the speed of sound has decreased by 10%, so the net result is an over-read of t_{echo} by 5%. Thus the liquid level appears lower. (In fact the foam comprises ≈ 2% liquid from the tank, but 2% of 5cm is negligible).

This can be compensated by sensors across the tank airspace, at a fixed spacing, to monitor the speed of sound. Also, we can put sensors under the liquid to measure the level ie. as in part d)

d) • Transit time of pulses in liquid is 4x less.

• Transducer energy coupling to liquid $= 1 - \left(\frac{1{\cdot}15\times10^6 - 3400}{1{\cdot}15\times10^6 + 3400}\right)^2$

$= 5{\cdot}9\times10^{-3}$ [cf: 0·33 to air]

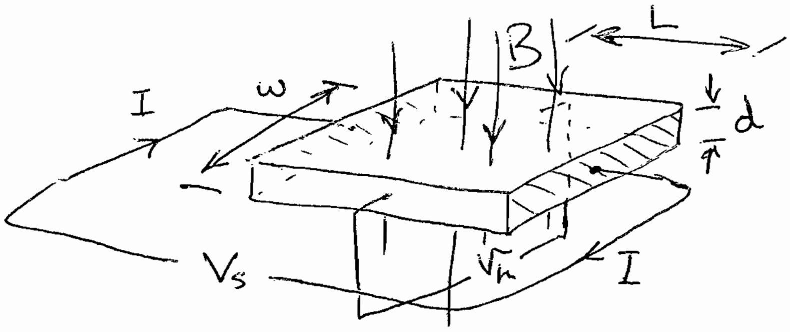
• Attenuation in liquid $-24\,dB \Rightarrow \times\, 4\times10^{-3}$ [cf 0·631 in air]

$\therefore$ Relative signal power $= \left(\frac{5{\cdot}9\times10^{-3}}{0{\cdot}33}\right)^2 \times \frac{4\times10^{-3}}{0{\cdot}631} = 2\times10^{-6}$

$\therefore$ recd. voltage drops by $\times\sqrt{2\times10^{-6}} = \times 1{\cdot}4\times10^{-3}$ (0·14%)

$\therefore$ $V_{sig} = 0{\cdot}60\,mV$

5a)



· A current is passed through a slice of semiconductor with the charge carriers being deflected by the magnetic field such that an electric field builds up across the slice (orthogonal to the current and magnetic flux). The electrostatic and magnetic forces balance in an equilibrium when the Hall voltage is established.

$$B q v_d = q \frac{V_h}{w}$$

Hall voltage
width
mag. flux density
carrier drift velocity
carrier charge

b) $F = \frac{e V_h}{w} = B e v_d$ where $I = n \underbrace{wd}_{\text{area}} v_d e$

carrier concent./density

$\therefore V_h = w B v_d = \frac{\cancel{w} B I}{n \cancel{w} d e} = \frac{B I}{n d e}$

To find carrier conc., n, we equate $v_d = \mu \frac{V_s}{L} = \frac{I}{n w d e}$

mobility

and given $R = \frac{V_s}{I} = \frac{\rho L}{w d} = \frac{L}{n w d e \mu}$ $\therefore \rho = \frac{1}{\mu n e}$

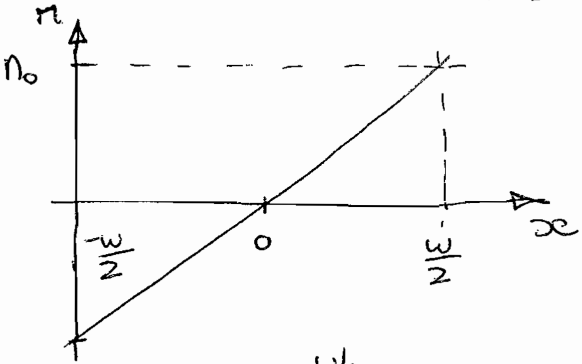
resistivity

or $n = \frac{1}{\rho \mu e}$ $\therefore V_h = \frac{B I \rho \mu \cancel{e}}{d \cancel{e}} = \frac{B I \rho \mu}{d}$

$V_h = \frac{0.01 \cdot 10^{-4} \cdot 0.045 \cdot 0.14}{10^{-6}}$ V

$V_h = 6.3$ mV

5c) If we assume a linear excess carrier concn. over the slice width:



$$n = \frac{2n_o}{w}x$$

$$\therefore \frac{dn}{dx} = \frac{2n_o}{w} \quad \text{---} *$$

N = total no. xs carriers one side $= Ld\int_0^{w/2} \frac{2n_o x}{w}\,dx = \frac{n_o w L d}{4}$ — *

Fick's Law of diffusion: F, carrier flux $= -D\frac{dn}{dx}$ where the diffusion coeff. $D = \frac{\mu k T}{q}$

Considering flow of carriers across centre from one side:

sub. from *s $\quad \frac{dN}{dt} = F \times \text{area} = FLd = -LDd\frac{2n_o}{w} = -\frac{8DN}{w^2}$

$$\therefore \frac{dN}{dt} = -\frac{8DN}{w^2}$$

1st order D.E. Soln. $N = N_o e^{-t/\tau}$ where $\tau = \frac{w^2}{8D}$

Hence $t_r^{10-90\%} = 2.2\tau = \frac{2.2w^2}{8D}$ ← $\frac{\mu k T}{e}$

$$\therefore t_r = \frac{1.1\,e\,w^2}{4\mu k T} = 7.6\text{ ns and}$$

$$f_{-3dB} = \frac{1}{\pi t_r} = 43\text{ MHz}$$

Assuming a max. velocity bead to travel 10μm in 7.6ns, then the velocity $= 10\times10^{-6}/7.6\times10^{-9} = 1316$ m/s ! (v. fast)

d) $R = \frac{\rho L}{wd} = 45\text{k}\Omega$, $V_n = \sqrt{4kTRB}$ with $B = 43\text{MHz}$

$$\therefore V_n = 0.18\text{ mV}_{rms}$$

Assume Sig./Noise = 1 then $\left(\frac{6.3}{0.18}\right)^{1/3} \times 5\mu m = 16.4\mu m$

(signal from 5μm range) ‖ (min. signal) (cube root)