Department of electronics design
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EL004A Sensor devices
2015-01-13

Written exam in Sensor Devices

Tentamen i Sensorkomponenter

Hjälpmedel: Miniräknare - *Aid*: Calculator

Basic part (50 % result compulsory for pass grade)

1 You have two types of magnetic sensors, one hall sensor and one magneto resistive sensor, how should you mount them for maximum sensitivity? (4 p)

2 Why do you (normally) need a rectifying contact in manufacturing a silicon detector for ionization radiation? (3 p)

3 What is the use of a catalyst/promoter in a chemical sensor? (3 p)

4 Why is it necessary to heat up gaseous detector of type tin-oxide? (4 p)

Calculation part

5 An amperometric biosensor is operated in the kinetic-limited mode. In this mode the substrate concentration in the enzyme layer is close to the bulk value. The enzyme process follows Michaelis-Menton kinetics. A measurements is giving

Substrate concentration 3 500 mol/cm^2
Enzyme concentration 0.003 mol/cm^2
Mediator concentration 0.002 mol/cm^2
Flux to electrode 2.20 x 10^9 mol/cm^2s
Membrane thickness 30 μm.

Under the assumption that the different processes contributing to the flux are equal at this measurement condition, what is the value of the different constants (or ratios of constants) that defines the process?

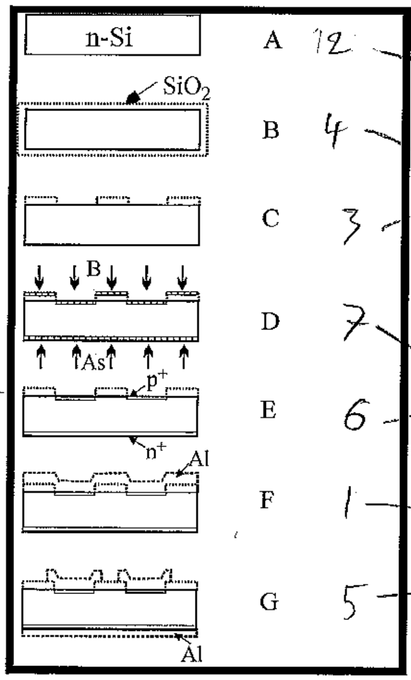
(5 p)

6 What is the resonant frequency for a silicon cantilever beam with the dimensions
length 1.2 mm
width 150 μm
thickness 6 μm (4 p)

7 How long does it take to grow a 700 Å thick layer of silicon-dioxide on a silicon sensor. Assume <100> crystal orientation, processing temperature 1000 °C and dry O_2 oxidization? Show detailed calculations!

(5 p)

8 Below the processing steps for a passivated planar silicon radiation detector is shown in figure and in text. Connect the figures to the right description for the processing steps to appear in right order.



1. Al metallisaton
2. n-Si Wafer
3. Opening of windows
4. Oxide passivation
5. Al pattering at the front
   Al rear contact
6. Annealing at 600° C, 30 min
7. Doping by ion implantation
   B 15 keV $5x10^{14}$ cm^{-2}
   As 30 keV $5x10^{14}$ cm^{-2}

(4 p)

9 A 300 μm thick silicon radiation sensor is used for detection of two radioactive sources. One source emits alfa-particles with the energy 4.5 MeV and the intensity 10000 particles/second. The second source emits gamma-photons with the same energy and intensity as the first source. Assume that all particles reach the detector and that all the sensor volume is active. Calculate the signal generated by the sensor for each source.

(6 p)

GOOD LUCK

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Appendix to exam in sensor devices

Semiconductor Sensor Technologies

Reactive growth

Result of the Deal-Grove model for growth of silicon dioxide

$$\tau = \frac{x_i^2 + Ax_i}{B} \qquad x_i \approx 0.02\mu m\,(200\mathring{A})$$

$$X_0 = \frac{A}{2}\left[\sqrt{1+\frac{t+\tau}{A^2/4B}}-1\right]$$

$$B = C_1 e^{-E_1/kT} \quad \textit{parabolic growth}$$

$$\frac{B}{A} = C_2 e^{-E_2/kT} \quad \textit{linear growth}$$

Boltzmann's constant: $k = 8.61739\cdot10^{-5}$ eV/K

Table 6–2 Rate constants describing (111) silicon oxidation kinetics at 1 Atm total pressure. For the corresponding values for (100) silicon, all C_2 values should be divided by 1.68.

Ambient	B	B/A
Dry O_2	$C_1 = 7.72 \times 10^2\ \mu m^2\ hr^{-1}$	$C_2 = 6.23 \times 10^6\ \mu m\ hr^{-1}$
	$E_1 = 1.23$ eV	$E_2 = 2.0$ eV
Wet O_2	$C_1 = 2.14 \times 10^2\ \mu m^2\ hr^{-1}$	$C_2 = 8.95 \times 10^7\ \mu m\ hr^{-1}$
	$E_1 = 0.71$ eV	$E_2 = 2.05$ eV
H_2O	$C_1 = 3.86 \times 10^2\ \mu m^2\ hr^{-1}$	$C_2 = 1.63 \times 10^8\ \mu m\ hr^{-1}$
	$E_1 = 0.78$ eV	$E_2 = 2.05$ eV

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Radiation sensors

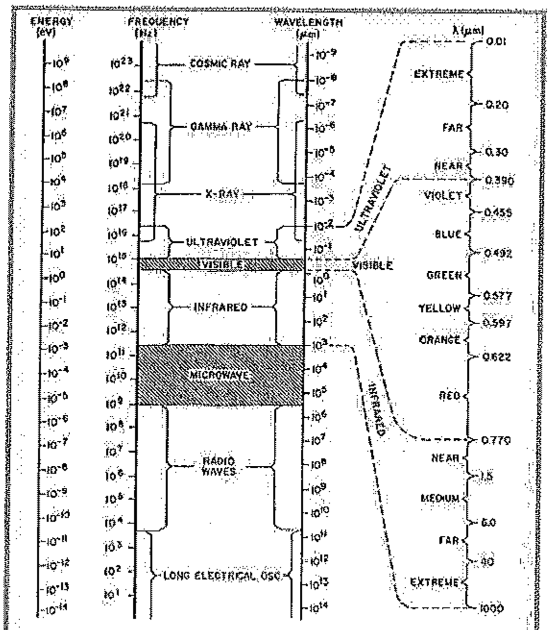


Fig. 1 Chart of electromagnetic spectrum. (After Ref. 4)

$$E = h\nu.$$

$$h = 6.626 \times 10^{-34} \text{ J-s.}$$

E=energy

ν=frequency

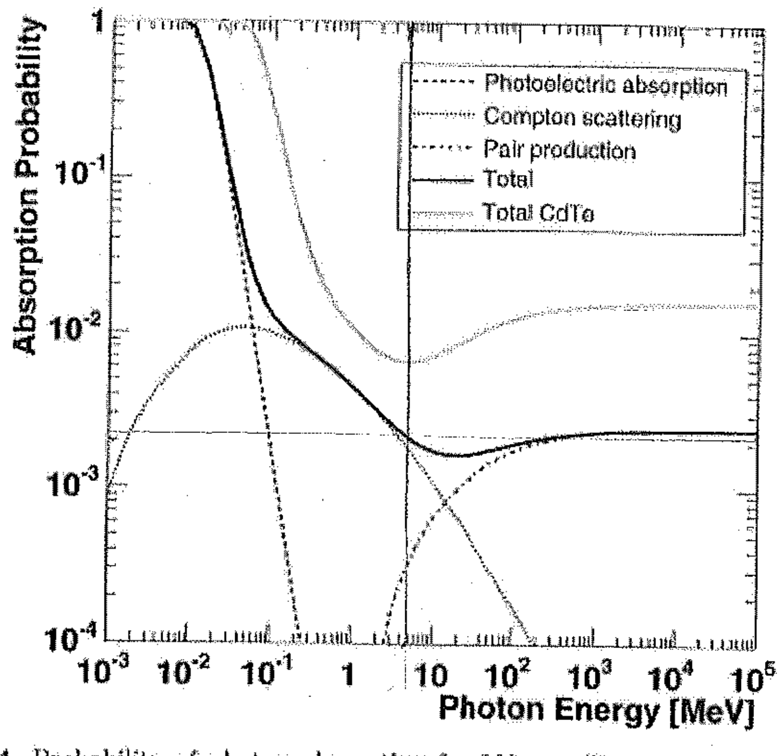


Fig. 2.4. Probability of photon absorption for 300 μm silicon as function of the photon energy. Contributions from different processes are indicated. The total absorption probability for 300 μm CdTe is also given for comparison (Data from [52])

The conversion factor for Si in room temperature is 3.62.
Electron charge: $q = 1.602 \cdot 10^{-19}$ C

Radiation Sensors and Thermal Sensors

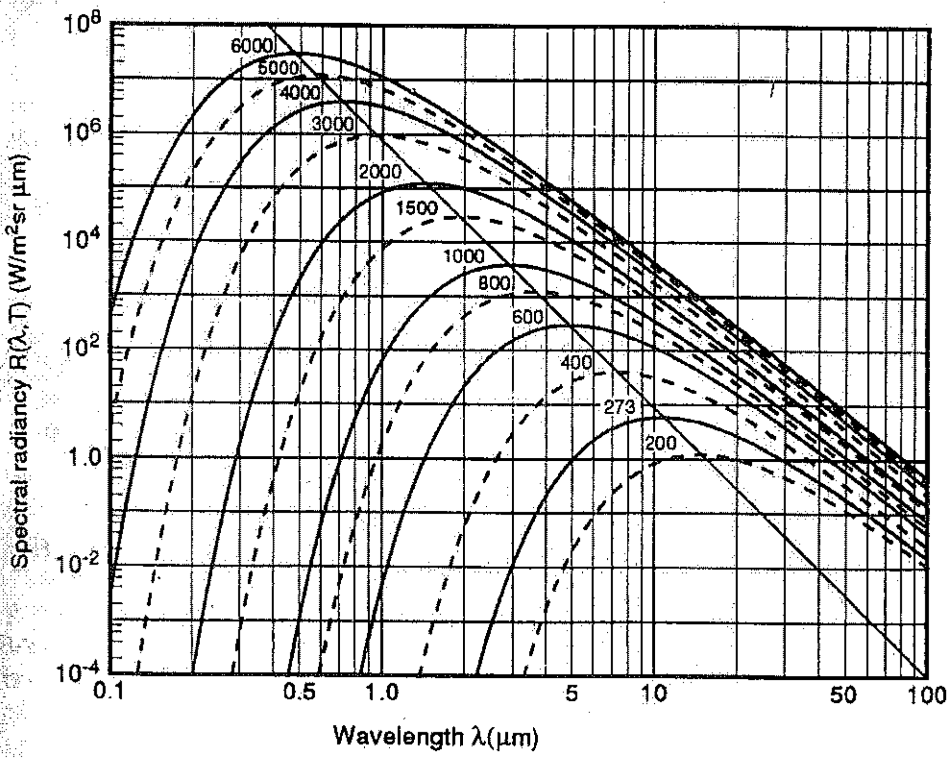


Fig. 4 Spectral radiancy (emitted power density per sr) $R(\lambda, T)$ of a black body at temperatures given in Kelvin. The diagonal line shows Wien's displacement law. (After Ref. 1)

Biosensors

Consider the case of the mediated enzyme electrode. The Michaelis–Menton kinetics, Eqs. 3 and 6, can be modified to the following form

$$S + E_O \underset{k_{-1}}{\overset{k_1}{\leftrightarrow}} E_O S \tag{35a}$$

and

$$E_O S \xrightarrow{k_2} P + E_R \tag{35b}$$

where E_O and E_R are the oxidized and reduced forms of the enzyme. The mediator reaction for the oxidation of the enzyme is

$$E_R + M_O \xrightarrow{k_e} E_O + M_R \tag{36a}$$

and the reaction for the oxidation of the mediator at the electrode is

$$M_R \to M_O + e^- \tag{36b}$$

where, again, M_O and M_R are the oxidized and reduced forms of the mediator. In this derivation, it is assumed that (1) the mediator oxidation at the electrode surface is very rapid, thus $[M_O] = [M]$, the total amount of added mediator, and (2) the enzyme layer is thin, so that the concentrations are uniform throughout the layer. The fluxes of the different species are: (i) for the membrane transport

$$j = k_D([S]_{\text{bulk}} - [S]) \tag{37a}$$

(ii) for the formation of the enzyme–substrate complex

$$j = l(k_1[E_O] - k_{-1}[E_O S]) \tag{37b}$$

(iii) for decomposition of the complex into the product and reduced enzyme

$$j = l k_2 [E_O S] \tag{37c}$$

and (iv) for the regeneration of the enzyme by the mediator

$$j = l k_e [E_R][M] \tag{37d}$$

where k_D is the membrane mass transport rate constant and l is the enzyme layer thickness. Under steady-state conditions, all of the fluxes are equal and the current is proportional to the flux, $i = nFj$, where n is the number of electrons in the mediator electrode reaction and F is the Faraday constant. If the enzyme concentration is fixed, $[E_{\text{tot}}]$, the following expression for the flux can be found[24]

$$\frac{1}{j} = \frac{K_M}{l k_2 [E_{\text{tot}}]\left([S]_{\text{bluk}} - \frac{j}{k_D}\right)} + \frac{1}{l k_2 [E_{\text{tot}}]} + \frac{1}{l k_e [M][E_{\text{tot}}]}. \tag{38}$$

The first term in Eq. 38 includes the effects of the Michaelis–Menton kinetics and the mass transport across the membrane. The second term is for the decomposition of the enzyme into the product and reduced enzyme. The last term describes the regeneration of the enzyme by the mediator. Any of these three terms can be the rate-limiting step.

As usual, this flux can be considered in two limiting cases. In the first case, assume that the decomposition of the enzyme–substrate complex and the oxidation of the reduced enzyme by the mediator are very rapid, and thus, the last two terms can be dropped. After rearrangement, Eq. 38 becomes

$$\frac{1}{j}=\frac{K_M}{lk_2[E_{tot}][S]_{bulk}}+\frac{1}{k_D[S]_{bulk}}. \tag{39}$$

In this case, the flux is proportional to the substrate concentration. The first term is due to the enzyme kinetics and the second is due to mass transport through the membrane. To make repeatable sensors that do not depend on the enzyme concentration or kinetics, the sensor should be used in the membrane diffusion limited case, where the first term can be neglected and the flux is proportional to the bulk substrate concentration.

In the second case, the diffusional flux is greater than the conversion of enzyme to product or the enzyme regeneration by the mediator. There will be a significant concentration of substrate in the enzyme layer and, in the limit, it can be assumed that $[S]_{bulk} \gg j/k_D$ and the concentration of substrate in the enzyme layer will be the bulk value. Equation 38 then reduces to

$$\frac{1}{j}=\frac{K_M}{lk_2[E_{tot}][S]_{bulk}}+\frac{1}{lk_s[E_{tot}]}+\frac{1}{lk_e[M][E_{tot}]}. \tag{40}$$

Here, the flux is very dependent on the concentration of the enzymes and mediator in the enzyme layer. In the reaction-limited operation, Eq. 40 can be used to determine rates of each step by varying one variable at a time, enzyme concentration, mediator concentration and the bulk substrate concentration.

The number of different enzymes used in amperometric biosensor is very large.[39] Some of the common substrates include glucose, urea, cholesterol, fructose, sucrose, and ethanol. Amperometric detection has also been used with tissues, and whole organisms.[41] In general, the detection limits of amperometric biosensors is about 10^{-9} to 10^{-8} M, with a linear range from 10^{-7} to about 10^{-3} M. The lifetimes of the amperometric biosensor depend on the biologically active material and the immobilization.

Extra formula sheeth: Sensor component exam 2015-01-13

Mechanical sensors

Table 19.1 Properties of materials

	Yield Strength (10^9 Pa)	Young's Modulus (10^9 Pa)	Density (g/cm^3)	Thermal Conductivity (W/cm °C)	Thermal Expansion (10^{-6}/°C)
Diamond (single crystal)	53.0	1035.0	3.5	20.0	1.0
SiC (single crystal)	21.0	700.0	3.2	3.5	3.3
Si (single crystal)	7.0	190.0	2.3	1.6	2.3
Al_2O_3	15.4	530.0	4.0	0.5	5.4
Si_3N_4 (single crystal)	14.0	385.0	3.1	0.2	0.8
Gold	—	80.0	19.4	3.2	14.3
Nickel	—	210.0	9.0	0.9	12.8
Steel	4.2	210.0	7.9	1.0	12.0
Aluminum	0.2	70.0	2.7	2.4	25.0

E: Young's Modulus

v: Poisson's ratio (= 0.28 for Si, ≈ 0.3 for most metals)

Cantilever beams

Cantilever beam uniform distributed load

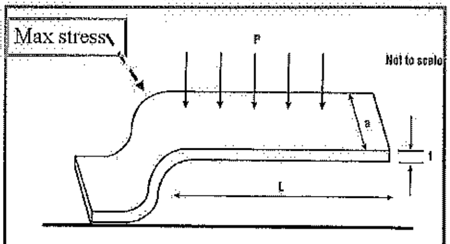


Figure 19.8 Cantilever beam fixed at one end, subjected to downward force per unit length P.

Uniform distributed load P (F is uniformed distributed over L)

$$P = F/a$$

I, bending of inertia "bending resistance"

$$I = \frac{at^3}{12}$$

Cantilever beam point load at the end

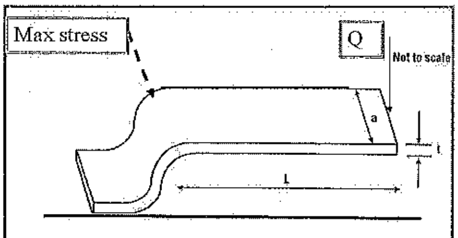


Figure 19.8 Cantilever beam fixed at one end, subjected to downward force per unit length P.

Deflection $W(P,x) = \frac{Qx^2}{6EI}(3L-x)$

Max stress $\sigma = QLt/2I$

Fundamental mode resonant frequency

$$F_o = 0.161\frac{t}{L^2}\left(\frac{E}{\rho}\right)^{1/2}$$

Cantilever beam mass M

$$F_o = 0.161\frac{t}{L}\left(\frac{Eta}{ML}\right)^{1/2}$$

Exam 150113

5 Substrate concentration $[S]_{bulk} = 3500$ mol/cm²

Enzyme conc. $[E_{tot}] = 0{,}003$ mol/cm²

Mediator conc. $[M] = 0{,}002$ mol/cm²

Flux $j = 2{,}2 \cdot 10^{9}$ mol/cm²s

Since "the substrate concentration in the enzyme layer is close to the bulk value" The Michaelis-Mention kinetics reduces to eq (40)

constants

$$\frac{1}{j} = \frac{K_M}{l k_2 [E_{tot}][S]_{bulk}} + \frac{1}{l k_s [E_{tot}]} + \frac{1}{l k_e [M][E_{tot}]}$$

Membrane thickness $l = 30\ \mu m = 3 \cdot 10^{-3}$ cm

$$1 = \frac{K_M}{k_2} \cdot \frac{2{,}2 \cdot 10^{9}}{0{,}003 \cdot 3500 \cdot 3 \cdot 10^{-3}} + \frac{1}{k_s} \frac{2{,}2 \cdot 10^{9}}{0{,}003 \cdot 3 \cdot 10^{-3}} +$$

$$\frac{1}{K_e} \frac{2{,}2 \cdot 10^{9}}{0{,}002 \cdot 0{,}003 \cdot 3 \cdot 10^{-3}}$$

Assume each sum equals $\frac{1}{3}$

$$\frac{K_M}{k_2} = 4{,}77 \cdot 10^{-12} \text{ mol s/cm}^3$$

$$\frac{1}{k_s} = 1{,}36 \cdot 10^{-15} \text{ s}$$

$$\frac{1}{k_e} = 2{,}73 \cdot 10^{-18} \text{ s}$$

Exam 15 01 13

6 See similar problem on lecture notes

Read $\rho = 2300\ kg/m^3$ from appendix

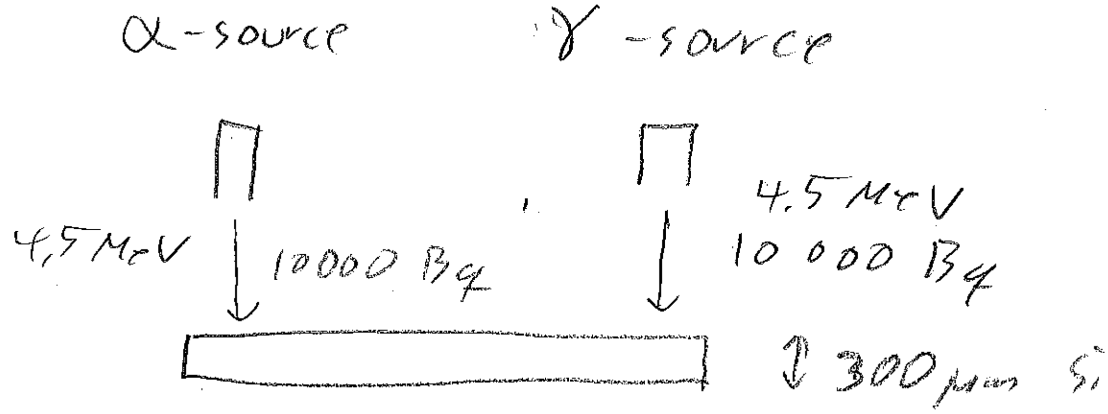
$$F_0 = 0{,}161 \cdot \frac{6 \cdot 10^{-6}}{(1{,}2 \cdot 10^{-3})^2} \cdot \sqrt{\frac{190 \cdot 10^9}{2300}}$$

$$= 6{,}10\ kHz$$

7 See similar problem on solution for exam 2010-04-28

Exam 150113

9



Alfa absorption is 100 %

Each alfa gives $4,5 \cdot 10^6 / 3,62 = 1,243 \cdot 10^6$

$I = 1,243 \cdot 10^6 \cdot 10000 \cdot 1,602 \cdot 10^{-19} = 2,00 \text{ nA}$

Gamma absorption can be read from Fig 2.4 in appendix. Gives approximately $2,1 \cdot 10^{-3}$

Absorbed count rate $10\,000 \cdot 2,1 \cdot 10^{-3} = 21$

Energy for each gamma and each alfa are equal.

$I = 1,243 \cdot 10^6 \cdot 21 \cdot 1,602 \cdot 10^{-19} = 4,18 \text{ pA}$