UNIVERSITY OF RUHUNA

Faculty of Engineering

End-Semester 5 Examination in Engineering: May 2023

Module Number: EE5305 **Module Name: Sensors and Transducers**

[3 Hours]

[Answer **all questions**, each question carries ten marks]

Q1 a) Compare the optical waveguiding of the two types of stripe geometries in the lateral structures of edge-emitting devices. Then, draw refractive index profiles in the lateral direction for each geometry and describe the reason for having such profiles.

[2.0 Marks]

b) A transparent substrate (TS) AlGaInP/GaP LED emits at 636 nm. It has an external quantum efficiency of $\eta_e = 23.7\%$ when operated at a forward voltage of 2.02 V with an injection current of 20 mA. Calculate the following parameters by considerIng that the photopic luminous efficiency at $\lambda = 636\ nm$ is 0.20816.

i. Power conversion efficiency under the given operating conditions.

[1.0 Mark]

ii. Optical output power.

[1.0 Mark]

iii. Luminous efficiency and luminous flux.

[1.0 Mark]

c) The refractive index of AlGaInP is $n = 3.4$. The AlGaInP LED surface is exposed directly to the air without any treatment. Transmittance T, is given by

$$T = \frac{4n_1 n_2}{(n_1 + n_2)^2}$$

i. Find the critical angle θ_c and the escape solid angle Ω_{esc} for the interface between AlGaInP and air. Calculate the transmittance of this surface?

[0.5 Marks]

ii. Find the escape efficiency η_{esc} using the calculated escape solid angle Ω_{esc} in the part i.

[0.5 Marks]

iii. Find η_{esc} using the approximate equation, and check the accuracy of the approximate equation to ensure that it provides a close approximation.

[1.0 Mark]

iv. Compare the escape efficiency with the external quantum efficiency of the AlGaInP/GaP LED described in part b)

[0.5 Marks]

v. Describe how to improve the extraction efficiency furthermore for both absorbing and transparent substrate.

[1.0 Mark]

vi. Explain methods for further improving the extraction efficiency for both absorbing and transparent substrate surface emitting LEDs. Discuss the maximum achievable extraction efficiency limits for each of these cases.

[1.5 Marks]

Q2 a) Consider direct band-to-band optical transitions in GaAs at $\lambda = 850$ nm wavelength at 300 K.

i. Calculate the reduced effective mass m_r^* for GaAs.

[1.0 Mark]

ii. Calculate the energy levels, E_2 and E_1, for the optical transitions at this wavelength.

[1.0 Mark]

iii. Calculate the value of the density of states $\rho(\nu)$ for these transitions.

[1.0 Mark]

iv. Given that $\tau_{sp} = 500\ ps$, calculate the spontaneous emission rate $R_{sp}(\nu)$ for intrinsic GaAs at this optical wavelength.

[1.0 Mark]

b) List three types of edge-emitting semiconductor LASERs and illustrate the structure of one of them.

[1.0 Mark]

c) Draw L-I characteristics and emission spectra for both LED and LASER, consider in both single mode and multimode LASER.

[1.0 Mark]

d) Calculate the detectivity and the specific detectivity of the Si photodetector which has an active area of $\mathcal{A} = 5\ mm^2$, a bandwidth of $B = 100$ MHz, and a dark current of $i_d = 10\ nA$, for the following two situations:
Hint: $(NEP)_{sh} = 1.13\ nW$ and $NEP = 364\ nW$

i. when the detector is shot-noise limited by its dark current with a large load resistance

[1.0 Mark]

ii. when the detector has a 50 Ω load resistance

[1.0 Mark]

e) Define the Coriolis force and draw a diagram that depicts the direction of the force, including all relevant physical quantities.

[2.0 Marks]

Q3 a) i. Briefly describe the Resistive Temperature Detector (RTD).

[0.5 Marks]

ii. List the wire-configurations for RTD and briefly explain each of them.
[2.0 Marks]

iii. Briefly explain the Seebeck effect.
[0.5 Marks]

iv. Explain what is Peltier effect and Thomson effect associated with thermocouples.
[1.0 Mark]

b) i. Figure Q3.b). illustrates a thermocouple. Write down an equation for generated voltage between two junctions by using the Peltier effect. Make sure to define all the notations which are used (eg: e_A = EMF generated at junction point A) and number the equation as Equation 1.
[1.0 Mark]

ii. Write down the equations for generated voltage across the metal wires by using the Thomson effect. Make sure to define all the notations which are used (eg: e_1 = EMF generated at the metal wire 1).
[2.0 Marks]

iii. Derive an equation for the resultant EMF generated due to Thomson effect. Number the equation as Equation 2.
[0.5 Marks]

iv. Combine the two effects together to derive an equation for the resultant EMF using Equation 1 and Equation 2.
[0.5 Marks]

v. Suppose you need to plan a practical test for above scenario. Identify the dependent and independent variables you are willing to use according to part iv.
[1.0 Mark]

c) Briefly explain how a dynamic loudspeaker operates. Sketch related diagram and name the key components.
[1.0 Mark]

Q4 a) Consider a police officer with a doppler radar gun that transmits a frequency of $F_{transmitting}$. A target-vehicle is moving at a speed of V_{target}. The reflected echo from the vehicle arrives with frequency $F_{received}$. Time delay is T_{R-T}.

i. Considering stationary source and moving observer, derive an equation for apparent frequency seen by the vehicle.
[1.0 Mark]

ii. Considering moving source and stationary observer, derive an equation for apparent frequency seen by the police officer (radar gun).
[0.5 Marks]

iii. Derive an equation for the doppler shift.
[0.5 Marks]

iv. Derive an equation for the doppler shift, if the vehicle is moving away from the police officer (radar gun).
[0.5 Marks]

v. Suppose, $V_{target} = 100\ km/hour$, $F_{transmitting} = 5GHz$, $T_{R-T} = 66\ \mu s$ and the vehicle is moving away from the police officer (radar gun). Note that the speed of the light, C = 3x10[8] ms^{-1}.

1. Calculate the doppler shift.

[0.5 Marks]

2. Calculate the distance to the target.

[0.5 Marks]

b) i. What does the acronym MEMS stand for?

[0.5 Marks]

ii. State the audible frequency range of the human ear.

[0.5 Marks]

c) Consider a capacitor with width = W, length = L and separation between plates = d as shown in the Figure Q4.b).

i. Evaluate the capacitance if one plate moves laterally by a distance **x** as shown in the Figure? Assume **d** keeps constant. Identify if the capacitance varies linearly with **x**.

[1.0 Mark]

ii. Suppose now only d is changing. While x remains the same, evaluate the new capacitance when the new separation between plates = d + Δ.

[1.0 Mark]

iii. Using Taylor series expansion, derive an equation to obtain linear approximation for part ii.
Note that the Taylor series of a function, $F_{(d)}$ can be approximated in the neighborhood of some nominal value d as,

$$F_{(d+\Delta)} = F_{(d)} + \frac{\Delta}{1!}.\frac{\partial F_{(d)}}{\partial d} + \frac{\Delta^2}{2!}.\frac{\partial^2 F_{(d)}}{\partial d^2} + \frac{\Delta^3}{3!}.\frac{\partial^3 F_{(d)}}{\partial d^3} + \cdots$$

[1.0 Mark]

iv. Using sketches and derivations, explain how differential capacitor works.

[1.5 Marks]

v. Sketch a diagram of a MEMS accelerometer and explain its operation.

[1.0 Mark]

Q5. a) Explain difference between voltage and power amplifier.

[2.0 Marks]

b) State differences between Class A, Class B, Class AB and Class C amplifier.

[2.0 Marks]

c) i. State the three main source of experimental uncertainties.

[1.0 Mark]

ii. A cart's kinetic energy is measured as k = 4.58 J ± 2%. Rewrite this finding in terms of its absolute uncertainty.

[1.0 Mark]

iii. In order to determine the quantity $q = x^2y - xy^2$, a scientist measures x and y as follows.
$x = 3.0 \pm 0.1$, $y = 2.0 \pm 0.1$
Evaluate his answer for q and its uncertainty?

[2.0 Marks]

iv. A meter stick can be read to the nearest millimeter; a traveling microscope can be read to the nearest 0.1 mm. Suppose you want to measure a length of 2 cm with a precision of 1%. Identify if this measurement can be obtained using meter stick or a traveling microscope. Explain your answer using necessary calculations.

[2.0 Marks]

Table Q2.a: Electronic properties of some intrinsic semiconductors at 300 K

	Effective mass		Mobility ($cm^2\ V^{-1}\ s^{-1}$)		Diffusion coefficient ($cm^2\ s^{-1}$)	
	m_e^*/m_0	m_h^*/m_0	μ_e	μ_h	D_e	D_h
Si	1.08	0.56	1350	480	35	12.5
Ge	0.55	0.31	3900	1900	100	50
GaAs	0.067	0.52	8500	400	220	10

Table Q2.b: Properties of some important semiconductors

Semiconductor		Type[c]	Bandgap, E_g (eV)		λ_g (nm)	Refractive index		Lattice constant (Å)
			At 0 K	At 300 K	At 300 K	At λ_g	At 1 μm	At 300 K
IV	C[d]	I	5.48	5.47	227	2.71	2.39	3.5668
	Si	I	1.17	1.12	1110	3.58	3.61	5.4310
	Ge	I	0.74	0.66	1880	4.12	4.38	5.6579
IV–IV	SiC	I	2.39–3.33	2.36–3.30	380–530	–	–	–
	Si_xGe_{1-x}	I	0.74–1.17	0.66–1.12	1110–1880	–	–	–
III–V[e]	AlN	D	6.29	6.20	200	2.80	2.17	$a = 3.112$ $c = 4.980$
	AlP	I	2.49	2.41	515	2.96	2.77	5.4635
	AlAs	I	2.23	2.17	572	3.19	2.95	5.6605
	AlSb	I	1.69	1.62	768	3.50	3.46	6.1355
	GaN	D	3.50	3.44	360	2.70	2.34	$a = 3.189$ $c = 5.185$
	GaP	I	2.34	2.26	549	3.43	3.17	5.4505
	GaAs	D	1.52	1.42	871	3.63	3.51	5.6533
	GaSb	D	0.81	0.73	1700	3.75	4.10	6.0959
	InN[f]	D	1.92	1.90	653	–	–	$a = 3.540$ $c = 5.800$
	InP	D	1.42	1.35	919	3.40	3.33	5.8687
	InAs	D	0.43	0.35	3540	3.52	3.63	6.0583
	InSb	D	0.24	0.17	7290	4.00	4.26	6.4794

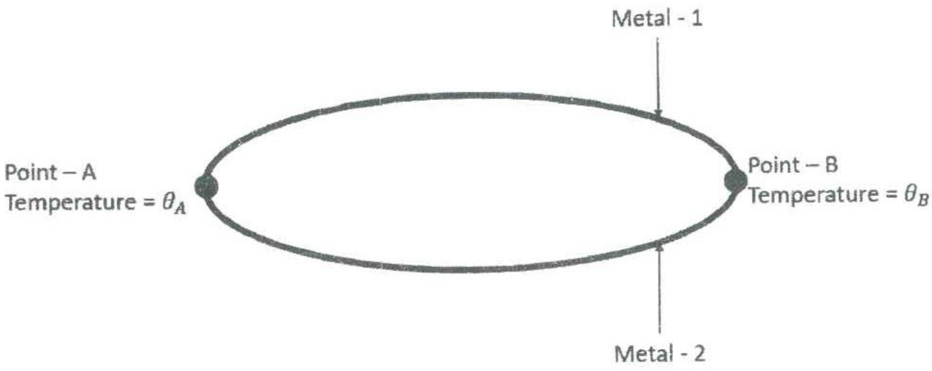

Figure Q3.b)

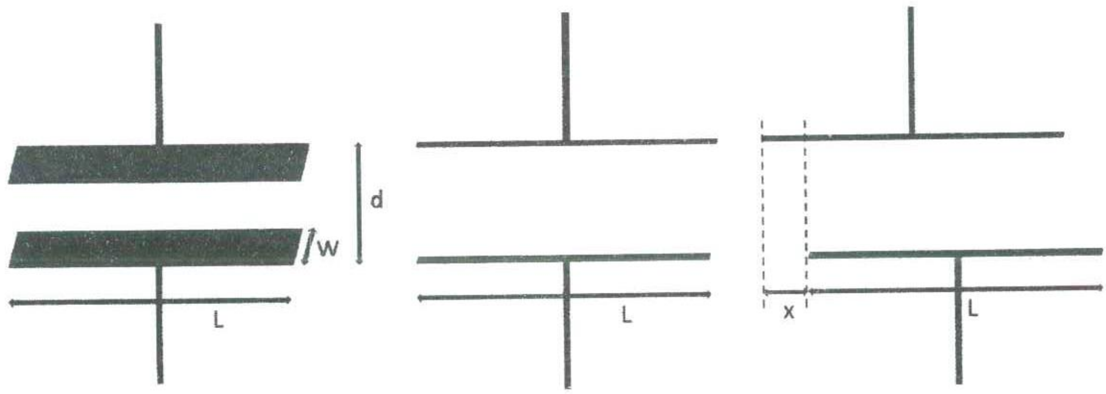

Figure Q4.b)