



SCHOOL OF COMPUTING AND ENGINEERING SCIENCES
BACHELOR OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING
END OF SEMESTER II 2025/2026 EXAMINATION
BEE 2202: ELECTRICAL MATERIALS

Date: 23rd March 2026

Time: 08.30 - 11.30 hours

Instruction:

1. This paper consists of **FIVE** questions.
2. Answer question 1 (**Compulsory**) and **ANY** other **TWO** questions
3. Show all your working in a systematic manner, where necessary, use diagrams to illustrate your concepts.
4. You may use your calculator

QUESTION 1 (30 MARKS)

- (a) Laser systems exhibit a number of distinctive characteristics that set them apart from conventional light sources. Describe any three (3) of these characteristics, explaining the physical basis of each. (3 marks)
- (b) Lasers have found widespread and transformative applications in the field of medicine. Describe **any three** specific applications of lasers in the medical field, explaining how the properties of laser light make each application effective. (3 marks)
- (c) Describe the concept of wave-particle duality. Use the de Broglie hypothesis to explain how matter can exhibit wave-like properties, and state the equation that relates wavelength to momentum. (3 marks)
- (d) An electron in a hydrogen atom is described by the quantum numbers $n = 4$, $l = 2$, $m_l = 0$, $m_s = -\frac{1}{2}$.
 - (i) Identify the orbital (subshell) occupied by this electron. (1 mark)
 - (ii) State the maximum number of electrons that can occupy this subshell and explain your answer using quantum numbers. (2 marks)
- (e) The Schrödinger equation is fundamental to quantum mechanics.
 - (i) Write the time-independent Schrödinger equation for a single particle and identify each term. (1 marks)

- (ii) Explain what is meant by a "state function" (wavefunction) and what physical information can be obtained from ψ^2 . (2 marks)
- (f) For the hydrogen atom, the principal quantum number (n) and the azimuthal quantum number (l) determine the energy and shape of atomic orbitals.
 - (i) List all possible values of l for an electron with $n = 3$. (1 mark)
 - (ii) For each value of l identified above, state how many orbitals exist and name the subshell. (1 mark)
- (g) The Stern-Gerlach experiment provided direct evidence for quantization of angular momentum.
 - (i) Describe the key observation from this experiment when a beam of silver atoms passed through an inhomogeneous magnetic field. (2 marks)
 - (ii) Explain what this result revealed about electron spin and spatial quantization. (2 marks)
- (h) Distinguish between a spectrophotometer and a spectrometer in terms of their primary function, output, and typical applications in chemical analysis. (3 marks)
- (i) Explain three (3) advantages of semi-conductor Lasers (3 marks)
- (j) Define "chemical shift" in NMR spectroscopy and explain why different hydrogen atoms in a molecule give signals at different chemical shift values. Include reference to electron shielding in your answer. (3 marks)

QUESTION 2 (15 MARKS)

- (a) Describe the three fundamental processes involved in laser operation: spontaneous emission, stimulated emission, and absorption. In your answer, explain which process is responsible for laser action. (4 marks)
- (b) Compare and contrast the operating principles of a ruby laser and a CO₂ laser based on the following parameters:
 - (i) The type of active medium used in each (2 marks)
 - (ii) The wavelength range of emission for each laser (1 mark)
 - (iii) One typical application for each type of laser (2 marks)
- (c) A semiconductor laser emits light at a wavelength of 650 nm.
 - (i) Calculate the energy of a single photon emitted by this laser in joules and in electron volts. ($h = 6.63 \times 10^{-34} \text{ J}\cdot\text{s}$, $c = 3.0 \times 10^8 \text{ m/s}$, $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$) (3 marks)
 - (ii) Calculate the frequency of this radiation. (1 mark)

- (d) Describe the basic working principle of a photodetector and explain why semiconductor materials are commonly used in photodetector devices. (2 marks)

QUESTION 3 (15 MARKS)

(a) Density Functional Theory (DFT) is one of the most widely used computational methods in quantum chemistry.

(i) Explain the fundamental principle of DFT and what physical property it calculates to determine molecular properties. (3 marks)

(ii) State two advantages of DFT over traditional wavefunction-based methods such as Hartree-Fock theory. (2 marks)

(b) Molecular building and geometry optimization are essential steps in computational chemistry.

(i) Describe the process of molecular building in computational chemistry software. What information must be specified to construct a molecular model? (2 marks)

(ii) Explain what is meant by "geometry optimization" and why it is necessary before performing energy calculations on a molecular system. (2 marks)

(c) Band structure theory is fundamental to understanding the electronic properties of solids.

(i) A semiconductor has a band gap of 1.8 eV. Calculate the maximum wavelength of light that can be absorbed by this semiconductor to promote an electron from the valence band to the conduction band. ($h = 6.63 \times 10^{-34} \text{ J}\cdot\text{s}$, $c = 3.0 \times 10^8 \text{ m/s}$, $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$) (2 marks)

(ii) Explain whether this semiconductor would be suitable for visible light detection and justify your answer. (1 mark)

(d) Spin-based quantum devices exploit the quantum mechanical property of electron spin.

(i) For an electron with spin quantum number $s = \frac{1}{2}$, calculate the magnitude of the spin angular momentum using the formula $|S| = \hbar\sqrt{s(s+1)}$, where $\hbar = 1.055 \times 10^{-34} \text{ J}\cdot\text{s}$. (2 marks)

(ii) Describe one challenge in designing spin-based quantum devices related to maintaining quantum coherence. (1 marks)

QUESTION 4 (15 MARKS)

(a) Using the Rydberg formula, calculate the wavelength of light emitted when an electron in a hydrogen atom transitions from $n = 4$ to $n = 2$.

(Rydberg constant $R_H = 1.097 \times 10^7 \text{ m}^{-1}$) (5 marks)

- (b) The photoelectric effect provided evidence for the particle nature of light.
- (i) A metal surface has a work function of 4.5 eV. Calculate the threshold frequency for this metal. ($h = 6.63 \times 10^{-34} \text{ J}\cdot\text{s}$, $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$) (3 marks)
 - (ii) If light of wavelength 250 nm strikes this metal surface, calculate the maximum kinetic energy of the ejected electrons. (3 marks)
- (c) Wave-particle duality is a fundamental concept in quantum mechanics.
- (i) Calculate the de Broglie wavelength of an electron traveling at $2.0 \times 10^6 \text{ m/s}$. (mass of electron = $9.11 \times 10^{-31} \text{ kg}$, $h = 6.63 \times 10^{-34} \text{ J}\cdot\text{s}$) (2 marks)
 - (ii) Compare this wavelength to that of a 1.0 kg object moving at 10 m/s and comment on the observability of wave properties in each case. (2 marks)

QUESTION 5 (15 MARKS)

- (a) Nuclear Magnetic Resonance (NMR) spectroscopy is a powerful analytical technique.
- (i) Explain why nuclei such as ^1H and ^{13}C are NMR-active while ^{12}C is not. Your answer should reference nuclear spin and angular momentum. (3 marks)
 - (ii) A proton in a magnetic field of 7.05 T resonates at a frequency of 300 MHz. Calculate the energy difference (ΔE) between the two spin states. ($h = 6.63 \times 10^{-34} \text{ J}\cdot\text{s}$) (2 marks)
- (b) Chemical shift is a key parameter in NMR spectroscopy.
- (i) Define chemical shift and explain why different hydrogen atoms in a molecule resonate at different frequencies. (3 marks)
 - (ii) A proton signal appears at 450 Hz downfield from TMS on a 300 MHz NMR spectrometer. Calculate the chemical shift (δ) in ppm. (2 marks)
- (c) The Schrödinger equation for a particle in a one-dimensional box of length L is given, with allowed energies $E_n = (n^2 h^2)/(8mL^2)$.
- (i) Calculate the energy of the $n = 3$ level for an electron confined in a box of length 1.0 nm. ($h = 6.63 \times 10^{-34} \text{ J}\cdot\text{s}$, $m_e = 9.11 \times 10^{-31} \text{ kg}$) (3 marks)
 - (ii) Calculate the wavelength of light emitted when the electron transitions from $n = 3$ to $n = 1$. (2 marks)