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Department of Physics, NTNU

Examination paper for FY3114 Functional materials

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Examination time (from-to): 9-13
Permitted examination support material:

- Alternative C, Approved pocket calculator
- K. Rottmann: Mathematical formulas (or equivalent)
- English dictionary

Students will find the examination results in Studentweb. Please contact the department if you have questions about your results. The Examinations Office will not be able to answer this.

1

P1-h2019

Strained Si transistors ....

Select one alternative

- will not exhibit changes in the electronic band structure
- cannot be used to enhance the density of charge carriers in p-doped transistors
- show increased optical scattering
- may result in increased mobility

Graphene transistors ....

Select one alternative

- are candidates for use in high speed computing applications
- have electron mobilities almost as high as in Si
- are easy to functionalize by chemical means
- utilize high effective mass electrons

High-K dielectric materials ....

Select one alternative

- can achieve similar capacitive and insulating properties as Si-oxide while being thinner
- result in increased leakage currents when used in transistors
- should have small band gaps when used in transistors
- are being used to downsize transistors

Which statement is correct?

Select one alternative

- the dielectric constant of a ferroelectric material is low
- a pyroelectric material is also ferroelectric
- a ferroelectric material is also pyroelectric and piezoelectric
- a piezoelectric material is also ferroelectric

(1 point for each correct answer)

Maximum marks: 4

2

P2-h2019

Topological transistors ....
Select one alternative:

- already have a wide range of applications
- are being used in quantum computation
- are conducting in the bulk
- are conducting at the surface

Organic Field Effect Transistors ....
Select one alternative

- are very stable under ambient conditions
- are being used in display technologies
- have by today overcome all performance challenges
- are expensive to fabricate

Carbon Quantum Dots ....
Select one alternative

- may not be used for bio-sensing
- have smaller band gap than Si or Ge
- may be an alternative to quantum dots made of expensive or toxic materials
- are relatively difficult to synthesize

Which of the following crystal systems are uniaxial?
Select one alternative

- cubic
- orthorombic
- tetragonal
- monoclinic

(1 point for each correct answer)

Maximum marks: 4

3

P3-h2019

Materials for optical storage ....
Select one alternative:

- can only be used in short lifetime storage devices
- must be good thermal conductors
- can be used in long lifetime storage devices
- can store more data if longer optical wavelengths are employed

Piezoelectric transistors...
Select one alternative

- are not suitable for use in touch devices
- may be made from centrosymmetric materials
- may be used as strain sensors
- represent a mature technology

Carbon Nanotube Transistors ....
Select one alternative

- show very high effective mass
- are complicated since the physics is not very well understood
- may provide fast switching for low electronic currents
- are hampered by strong electron scattering

Multiferroic materials for storage devices ....
Select one alternative

- may be found in the class of perovskites
- represents a mature field of engineering
- may be metallic, semiconducting or insulating
- cannot be used for Random Axcess memory (RAM)

(1 point for each correct answer)

Maximum marks: 4

4

P4-h2019

Find the angle of rotation around the z-axis which diagonalize a symmetric 2nd rank tensor of a monoclinic system. The tensor elements are given to be T_{11}=5.0, T_{22}=2.0, and T_{12}=4.0.

Select one alternative

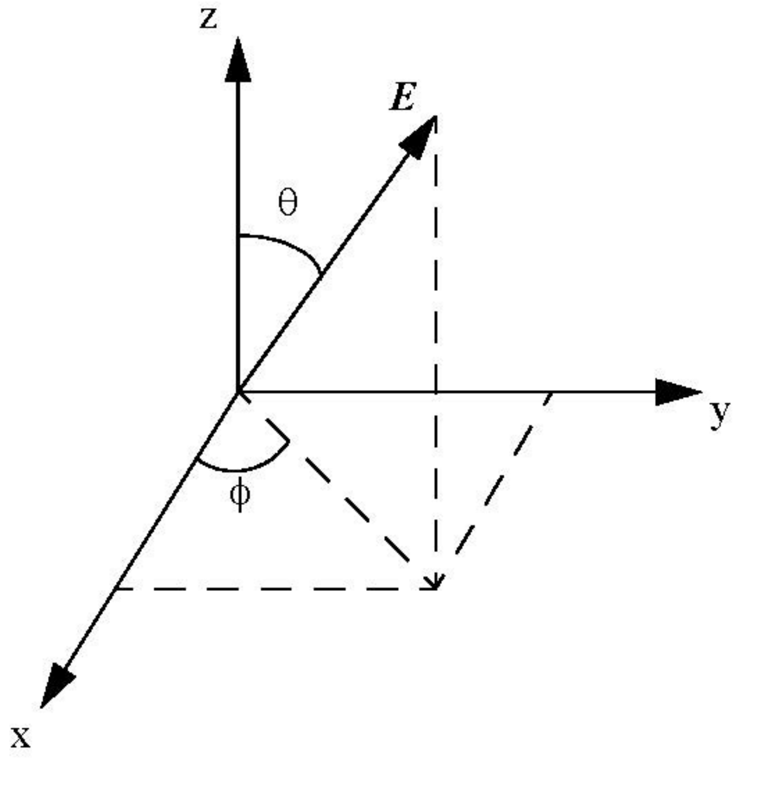
- 37.4^o
- 62.1^o
- 45.0^o
- x 34.7^o
- 28.3^o

(4 points for correct answer)

Maximum marks: 4

5

P5-h2019



An electric field ***E*** as shown in the figure acts on an orthorhombic dielectric material. The ***E*** field is at an angle of θ = 30° with the z-axis, and the projection of the field in the xy-plane is at an angle ϕ = 60° with the x-axis. Find the dielectric permittivity in the direction of the E field in terms of the components of the dielectric tensor: ϵ_{11} = 8.0 , ϵ_{22} = 6.0 and ϵ_{33} = 4.0 in units of $10^{-10} kg^{-1} m^{-3} s^4 A^2$.

Select one alternative:

- $3.5 \cdot 10^{-10} kg^{-1} m^{-3} s^4 A^2$
- $2.425 \cdot 10^{-10} kg^{-1} m^{-3} s^4 A^2$
- $4.625 \cdot 10^{-10} kg^{-1} m^{-3} s^4 A^2$
- $3.65 \cdot 10^{-10} kg^{-1} m^{-3} s^4 A^2$
- $5.28 \cdot 10^{-10} kg^{-1} m^{-3} s^4 A^2$

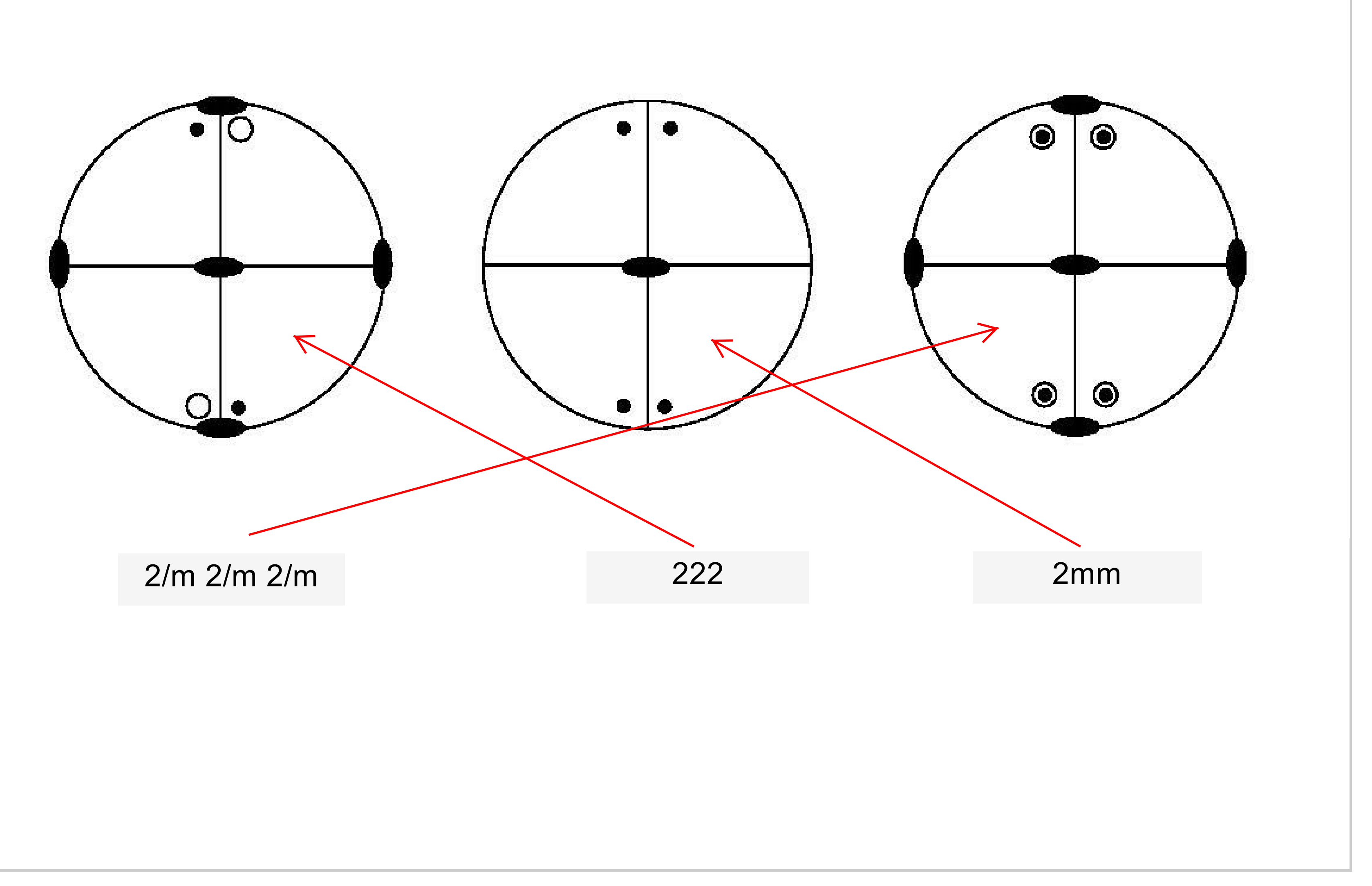
(4 points for correct answer)

Maximum marks: 4

6 P6-h2019

Identify the stereograms (2D pointgroup projections) by placing the relevant point group notations on top of the stereograms.

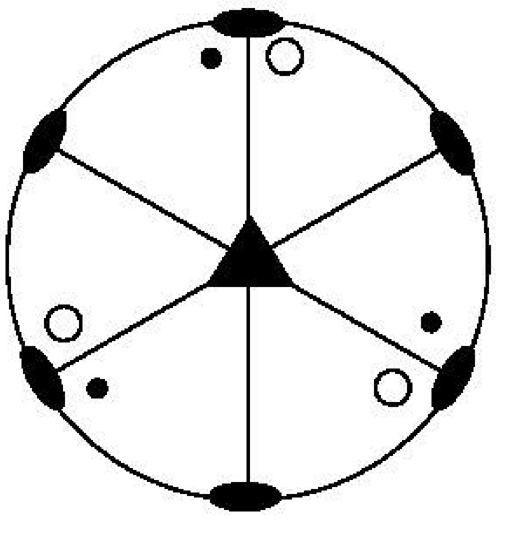
Move the point group notations listed at the bottom on top of the relevant stereogram



(1 point for each correct answer)

Maximum marks: 3

7 P7-h2019



To which point group does the stereogram above correspond?

Select one alternative:

- $\bar{3}2/m$
- $\bar{6}m2$
- 32
- $3m$

(2 points for correct answer)

Maximum marks: 2

8
P8-h2019

Which ones of the points groups 2/m 2/m 2/m, 222, 2mm, 6/m, 3m, 422 and 4/m mm are enantiomorphous (do not contain a mirror plane or a center of symmetry)?

Select one or more alternatives:

- 2mm
- 4/m mm
- 6/m
- → 222
- 2/m 2/m 2/m
- 3m
- → 422

(2 points for correct answer, -1 point for wrong answer, 0 points for no answer, minimum score is 0 points)

Maximum marks: 4

9
P9-h2019

GaAs has a band gap of 1.41 eV at room temperature (300 K). Find the energy of the electron and hole relative to the relevant band edges that results when a 1.7 eV photon is adsorbed.

The energy of the electron is:

Select one alternative

- 0.40 eV
- → 0.25 eV
- 0.32 eV
- 0.15 eV
- 0.52 eV

The energy of the hole is:

Select one alternative

- -0.35 eV
- → -0.038 eV
- -0.025 eV
- -0.15 eV
- -0.042 eV

(2 point for each correct answer)

Maximum marks: 4

10 P10-h2019

Consider a Si semiconductor at temperature 300 K which can emit optical phonons of energy ϵ_{phonon}=50 meV under the influence of an electric field ***E***. The electron scattering relaxation time τ_{sc}= $1 \cdot 10^{-13}$ s. Calculate the electric field at which the electron can emit optical phonons on the average. The total kinetic energy of the electron may be assumed to be described by the drift velocity and the thermal energy.

18

Enter your answer here: 18 kV/cm.

(4 points for correct answer)

Maximum marks: 4

11 P11-h2019

The average electric field in a Si device of length 3 μm is 20 kV/cm. The temperature may be assumed to be 300 K.

Calculate the transit time of an electron through the device using the low field value of the mobility.
Select one alternative:

- $1.5 \cdot 10^{-13} s$
- $1.5 \cdot 10^{-12} s$
- $3.0 \cdot 10^{-13} s$
- $3.0 \cdot 10^{-11} s$
- → $1.5 \cdot 10^{-11} s$

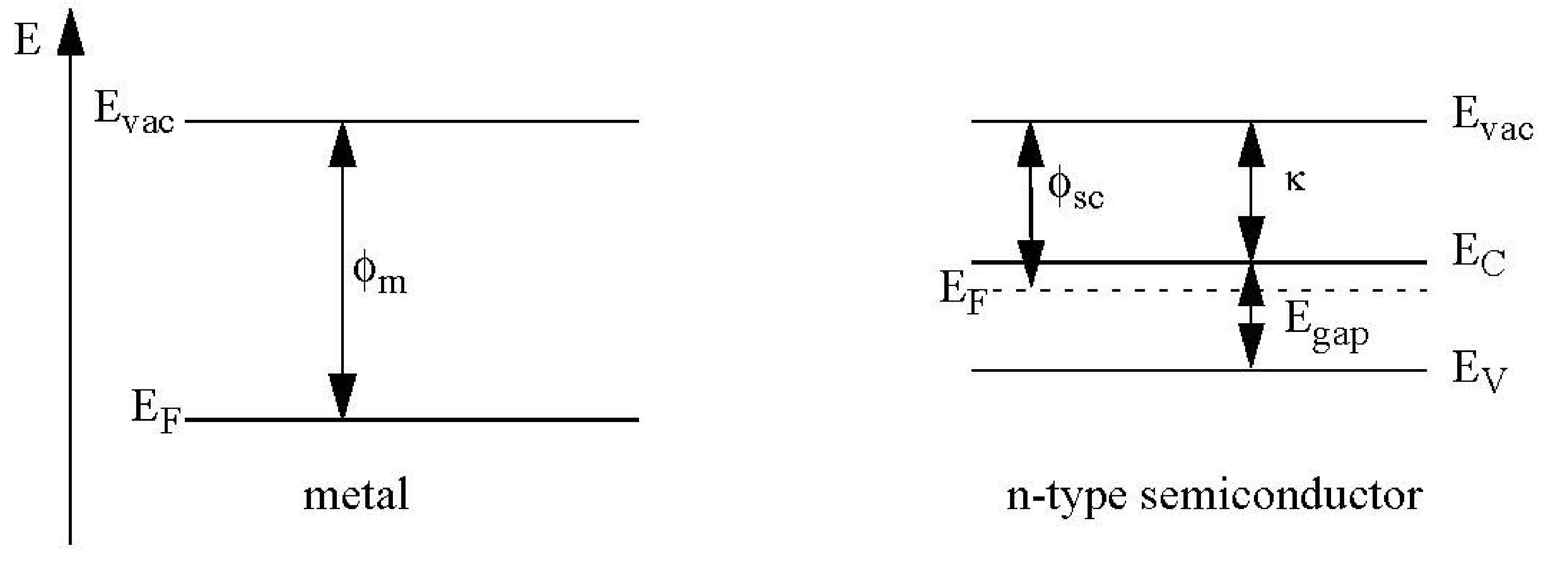
Calculate the transit time of an electron through the device using the saturation value of $1 \cdot 10^{-7} cm/s$ of the drift velocity.
Select one alternative

- $1.5 \cdot 10^{-13} s$
- $1.5 \cdot 10^{-12} s$
- $3.0 \cdot 10^{-13} s$
- → $3.0 \cdot 10^{-11} s$
- $1.5 \cdot 10^{-11} s$

(1 point per correct answer)

Maximum marks: 2

12 P12-h2019



The schematic representation above shows the energy levels of a metal (left) and an n-type semiconductor (right). The work functions of the metal and the semiconductor are given by $\Phi_m = 5.0$ and $\Phi_{sc} = 3.9$ eV; respectively. The energy gap of the semiconductor is $E_{gap} = 1.4$ eV, and the electron affinity $\chi = 3.2$ eV.

What is the barrier height when metal and semiconductor are contacted?

Write the answer here 1.8 eV.

What kind of contact is formed?

Select one alternative

- Schottky contact
- none of the above
- Ohmic contact

(2 points for each correct answer)

Maximum marks: 4

13 P13-h2019

Soft ferromagnetic materials may be used for:
Select one or more alternatives:

- Transformers
- Magnetic recording devices
- Motors
- Induction ovens
- Flux guides
- Permanent magnets
- Magnetic shielding

(1 point for correct answer, -1 point for wrong answer, 0 points for no answer, minimum score is 0 points)

Maximum marks: 3

14 P14-h2019

Silicon is an electro-optic active material in the cubic point group *m3m*, and has inversion symmetry. An electric field ***E*** is applied in the z-direction. The refractive index in the absence of an electric field is ***n***. The influence of the electric field on the impermeability tensor is given by the Kerr effect.

$\eta_{ij}(E) = \eta^0_{ij} + \sum_{kl} s_{ijkl} E_k E_l$, where $\eta^0_{11} = \eta^0_{22} = \eta^0_{33} = 1/n^2$, and other $\eta^0_{ij} = 0$

The only non-zero elements of the fourth rank tensor are
$s_{11} = s_{22} = s_{33}, s_{12} = s_{13} = s_{23}, s_{44} = s_{55} = s_{66}$ (using contracted notation).

What is the difference of the extraordinary and ordinary index of refraction $\Delta n = n_e - n_o$?
Select one alternative:

- $\frac{1}{2} n^3 E^2 (s_{12} - s_{11})$
- $\frac{1}{2} n^3 E^2 (s_{11} - s_{44})$
- $\frac{1}{2} n E^2 (s_{12} - s_{11})$
- $\frac{1}{2} n E^2 (s_{12} - s_{44})$
- $\frac{1}{2} n^3 E^2 (s_{12} - s_{44})$

(4 points for correct answer)

Maximum marks: 4

15 **P15-h2019**

The piezoelectric tensor of the tetragonal material PZT-5H (point group 4mm) is given by:

$$d = \begin{bmatrix} 0 & 0 & 0 & 0 & 735 & 0 \\ 0 & 0 & 0 & 735 & 0 & 0 \\ -263 & -263 & 515 & 0 & 0 & 0 \end{bmatrix}$$ in units of $10^{-12} C/N$

The polarization along the x-axis for a shear stress $\sigma = 1 \cdot 10^4 Nm^{-2}$ around the x-axis is:
Select one alternative

- → 0
- $7.35 \cdot 10^{-6} Cm^{-2}$
- $-2.63 \cdot 10^{-6} Cm^{-2}$
- $3.46 \cdot 10^{-6} Cm^{-2}$
- $-3.46 \cdot 10^{-6} Cm^{-2}$

The polarization along the x-axis for a shear stress $\sigma = 1 \cdot 10^4 Nm^{-2}$ around the y-axis is:
Select one alternative

- → $7.35 \cdot 10^{-6} Cm^{-2}$
- 0
- $-2.63 \cdot 10^{-6} Cm^{-2}$
- $2.63 \cdot 10^{-6} Cm^{-2}$
- $3.46 \cdot 10^{-6} Cm^{-2}$

The polarization along the z-axis for a normal stress $\sigma = 1 \cdot 10^4 Nm^{-2}$ along the y-axis is:
Select one alternative:

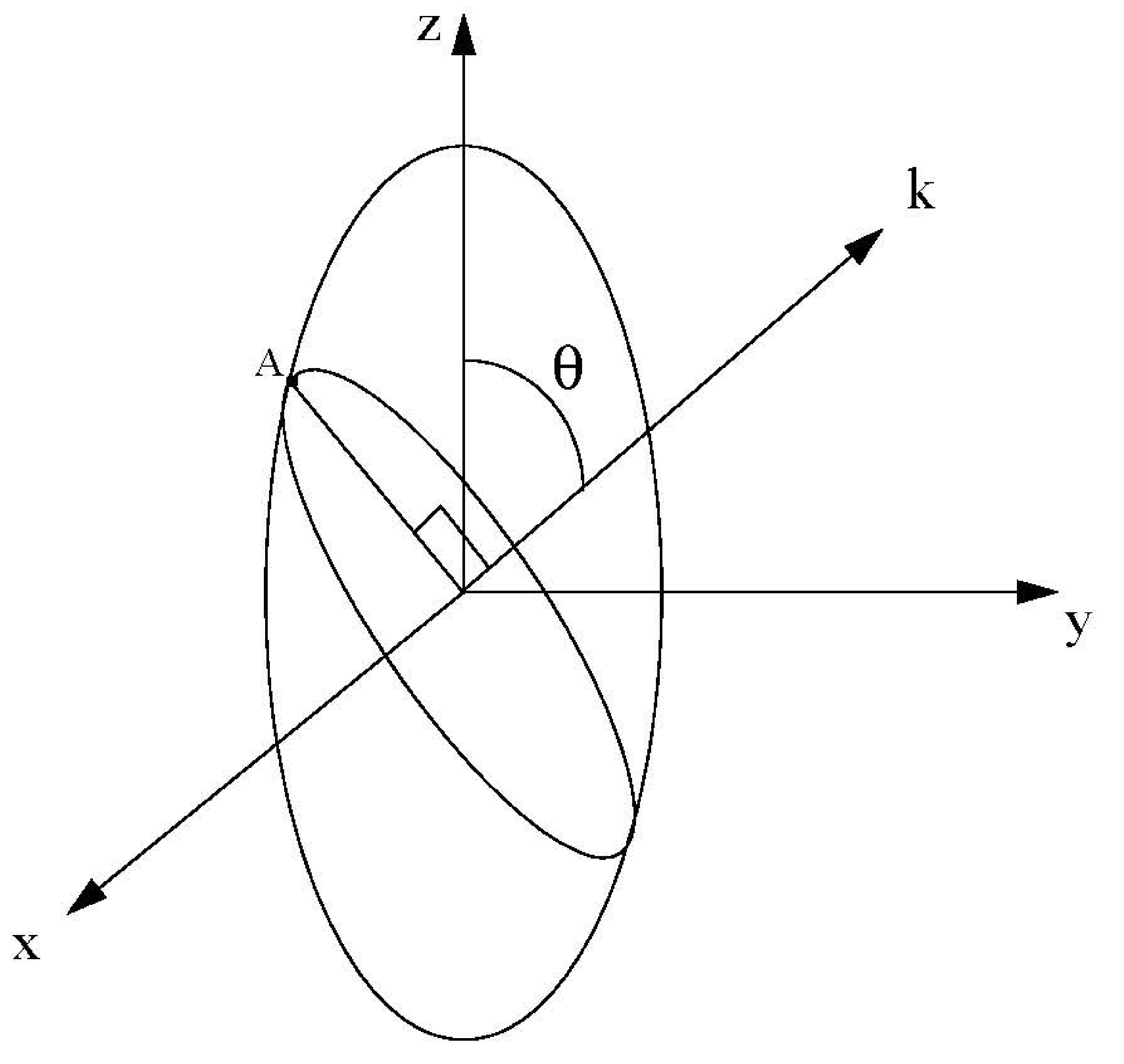
- 0
- → $-2.63 \cdot 10^{-6} Cm^{-2}$
- $7.35 \cdot 10^{-6} Cm^{-2}$
- $3.46 \cdot 10^{-6} Cm^{-2}$
- $2.63 \cdot 10^{-6} Cm^{-2}$

(1 point for each correct answer)

Maximum marks: 3

16

P16-h2019



The figure above shows the index ellipsoid of a uniaxial optical active material. The propagation direction of the light is perpendicular to the ellipse as shown. The wave vector ***k*** is in the yz-plane. The point A is located in the yz-plane and on both the ellipsoid and the ellipse. The angle $\theta = 55^0$, and the ordinary and extraordinary indices of refraction are$n_o = 1.85$ and $n_e = 1.65$.

What is the refractive index $n_e(\theta = 55^0)$?

Enter the answer here: 1.71.

(4 points for correct answer)

Maximum marks: 4

17

P17-h2019

A solar cell consists of a GaAs pn-diode of area $A = 1cm^2$. The temperature is 300 K. The total current of the diode connected to an external load is given by

$$I = I_L - I_0(e^{eV/k_BT} - 1)$$

where I_L is the photocurrent and I_0 is the diffusion current of electrons and holes. Find the open circuit $(I = 0)$ voltage V_{OC} for the solar cell.
Parameter values are:

Density of electrons and holes: $n_n = 1 \cdot 10^{16} cm^{-3}$ and $p_p = 1 \cdot 10^{17} cm^{-3}$
Electron diffusion coefficients: $D_n = 25.0cm^2/s$ and $D_p = 12.1cm^2/s$
Electron and hole recombination times: $\tau_n = 1 \cdot 10^{-8} s$ and $\tau_p = 1 \cdot 10^{-7} s$
Photocurrent: $I_L = 20mA$

The open circuit voltage V_{OC} is:
Select one alternative:

- 0.67 V
- 0.97 V
- 0.44 V
- 0.53 V
- 0.25 V

(4 points for correct answer)

Maximum marks: 4

Some potentially useful constants and formulas

Constants and numerical values (densities and mobilities at 300 K):			
$m_e = 9.1\cdot 10^{-31}$ kg,	$e = 1.6\cdot 10^{-19}$ C,	$k_B = 1.38\cdot 10^{-23}$ J/K $= 8.617\cdot 10^{-5}$ eV/K,	$h = 6.63\cdot 10^{-34}$ Js
n_i(Si) $= 1.5\cdot 10^{10}$ cm^{-3},	μ_n(Si) = 1000 cm^2/Vs,	μ_p(Si) = 350 cm^2/Vs (low field values)	
n_i(GaAs) $= 1.84\cdot 10^{6}$cm^{-3},	μ_n(GaAs) = 8000 cm^2/Vs,	μ_p(GaAs) = 400 cm^2/Vs (low field values)	
m_e*(GaAs) = 0.067m_e ,	m_h*(GaAs) = 0.45m_e ,	m_e*(Ge) = 0.56m_e ,	m_h*(Ge) = 0.29m_e
m_e*(Si) = 0.26m_e,	m_h*(Si) = 0.5m_e ,	m_e*(InP) = 0.07m_e,	m_h*(InP) = 0.4m_e

Rotation matrix R:

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad and \quad \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}$$

Transformation of tensors:

$$T_{ij}' = \sum_{kl} R_{ik} R_{jl} T_{kl} \quad and \quad T_{ijk}' = \sum_{lmn} R_{il} R_{jm} R_{kn} T_{lmn}$$

Transformation of products of coordinates:

$$x_i' x_j' = \sum_{kl} R_{ik} R_{jl} x_k x_l \quad and \quad x_i' x_j' x_k' = \sum_{lmn} R_{il} R_{jm} R_{kn} x_l x_m x_n$$

Dielectric permittivity tensor:

$$\varepsilon_{triclinic} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{12} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{13} & \varepsilon_{23} & \varepsilon_{33} \end{bmatrix} \quad \varepsilon_{monoclinic} = \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & 0 \\ \varepsilon_{12} & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \quad \varepsilon_{orthorhombic} = \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix}$$

$$\varepsilon_{tetragonal} = \varepsilon_{trigonal} = \varepsilon_{hexagonal} = \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{11} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \quad \varepsilon_{cubic} = \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{11} & 0 \\ 0 & 0 & \varepsilon_{11} \end{bmatrix}$$

Conductivity, drift velocity, mobility, diffusion coefficient, and diffusion current for electron:

$$\sigma = ne^2\tau_{sc}/m^* = ne\mu \qquad \boldsymbol{v_d} = \mu\boldsymbol{E} \qquad \mu = e\tau_{sc}/m^* \qquad D_n = \mu_n k_B T/e \qquad J_{diff} = eD_n\frac{dn}{dx}$$

Diffusion lengths for electron and holes:

$$L_n = \sqrt{D_n\tau_n} \quad and \quad L_p = \sqrt{D_p\tau_p}$$

Electrons and holes in semiconductors:

$$n = N_c e^{-(E_c - E_F)/k_B T} \qquad p = N_v e^{-(E_F - E_v)/k_B T} \qquad np = N_c N_v e^{-E_{gap}/k_B T} \qquad N_c = 2\left(\frac{m_e^* k_B T}{h^2/2\pi}\right)^{3/2} \qquad N_v = 2\left(\frac{m_h^* k_B T}{h^2/2\pi}\right)^{3/2}$$

Emission:

$$\hbar\omega = E_e - E_h = E_{gap} + \frac{(\hbar k)^2}{2m_r^*} \qquad W_{em}^{st}(\hbar\omega) = \frac{e^2 n_r \hbar\omega}{3\pi\varepsilon_0 m_e^2 c^3 \hbar^2}|p_{cv}|^2 \cdot n_{ph}(\hbar\omega) \qquad \frac{2|p_{cv}|^2}{m_e} = 23eV \quad (GaAs)$$

Law of mass action:

$$n_n \cdot p_n = n_i^2 = n_p \cdot p_p$$

Solution Exam Dec.17, 2019.

Problem 1 Project relevant questions: xxxx
Problem 2 Project relevant questions: xxxx
Problem 3 Project relevant questions: xxxx

Problem 4
Find the angle of rotation around the z-axis which diagonalize a symmetric 2nd rank tensor of a monoclinic system. The tensor elements are given to be T_{11}=5.0, T_{22}=2.0, and T_{12}=4.0.

Will diagonalize a 2nd rank monoclinic tensor by rotation.

$$T_{monoclinic} = \begin{bmatrix} T_{11} & T_{12} & 0 \\ T_{12} & T_{22} & 0 \\ 0 & 0 & T_{33} \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

$$\text{therefore} \quad x'y' = (yy - xx)\sin\theta\cos\theta + xy(\cos\theta\cos\theta - \sin\theta\sin\theta)$$

$$\text{and} \quad T'_{12} = (T_{22} - T_{11})\frac{\sin 2\theta}{2} + T_{12}\cos 2\theta$$

For $T'_{12} = 0$ we get:

$$\tan 2\theta = \frac{2T_{12}}{T_{11} - T_{22}} = 1 \Rightarrow \theta = 34,7^o$$

Problem 5
The dielectric tensor of an orthorhombic solid is given by

$$\varepsilon_{trigonal} = \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \quad and \quad \begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

The dielectric constant along the direction of the electric field is given by

$$\varepsilon_E = D_E/E = \frac{D \cdot E}{E^2} = \sum_i D_i E_i / E^2 = \sum_{ij} \varepsilon_{ij} \frac{E_j E_i}{E\ E}$$

then we get

$$\varepsilon_E = \varepsilon_{11}\left(\frac{E_x}{E}\right)^2 + \varepsilon_{22}\left(\frac{E_y}{E}\right)^2 + \varepsilon_{33}\left(\frac{E_z}{E}\right)^2$$

From the figure we see

$$E_x = E\sin\theta\cos\phi \qquad E_y = E\sin\theta\sin\phi \qquad E_z = E\cos\theta$$

which gives when $\theta = 30^o$ and $\phi = 60^o$ and e_{11}=8.0, e_{22}=6.0, e_{33}=4.0 in units 10^{-10} $kg^{-1}m^{-3}s^4A^2$

$$\varepsilon_E = \varepsilon_{11}(\sin\theta\cos\phi)^2 + \varepsilon_{11}(\sin\theta\sin\phi)^2 + \varepsilon_{33}(\cos\theta)^2$$

$$\varepsilon_E = \varepsilon_{11}\left(\frac{1}{2}\frac{1}{2}\right)^2 + \varepsilon_{22}\left(\frac{1}{2}\frac{\sqrt{3}}{2}\right)^2 + \varepsilon_{33}\left(\frac{\sqrt{3}}{2}\right)^2 = \frac{\varepsilon_{11}}{16} + \frac{3\varepsilon_{22}}{16} + \frac{3\varepsilon_{33}}{4} = 4,625 \cdot 10^{-10} kg^{-1} m^{-3} s^4 A^2$$

Problem 6 See table of stereograms.
Problem 7 See table of stereograms.
Problem 8 See list of crystallographic point groups.

Problem 9
GaAs has band gap of 1.41 eV at a temperature of 300 K. Find the energy of the electron and hole (relative to the respective band edge) that results when a 1.7 eV photon is adsorbed.

A photon is absorbed by GaAs and thus creates an electron in the conduction band and a hole in the valence band. By using the reduced mass we may write

$$\hbar\omega = E_e - E_h = E_{gap} + \frac{(\hbar k)^2}{2m_r^*} \qquad and \qquad E_e = E_c + \frac{(\hbar k)^2}{2m_e^*} \qquad and \qquad E_h = E_v - \frac{(\hbar k)^2}{2m_h^*}$$

The energies of the electron and hole become

$$E_e - E_c = \frac{m_r^*}{m_e^*}(\hbar\varpi - E_{gap}) = \frac{0{,}0583}{0{,}067}(1{,}7 - 1{,}41) = 0{,}25eV$$

$$E_h - E_v = -\frac{m_r^*}{m_h^*}(\hbar\varpi - E_{gap}) = \frac{-0{,}0583}{0{,}45}(1{,}7 - 1{,}41) = -0{,}038eV$$

Problem 10
Si semiconductor emits 50 meV phonons under influence of an electric field. Electron effective mass $m^*=0.26m_e$. Electron scattering time $\tau_{sc}=10^{-13}$s. The electron kinetic energy becomes:

$$\varepsilon = \frac{1}{2}m^* v_d^2 + \frac{3}{2}kT \qquad where \qquad v_d = \mu E \qquad and \qquad \mu = \frac{e\tau_{sc}}{m^*}$$

$$\frac{1}{2}m^* v_d^2 = \varepsilon - \frac{3}{2}kT = 50 - 39 = 11meV \qquad and \qquad v_d = 1{,}22 \cdot 10^5 \frac{m}{s}$$

$$E = \frac{m^* v_d}{e\tau_{sc}} = 18{,}04 \cdot kV/cm$$

Problem 11
The average electric field in a Si device of length 3mm is 20 kV/cm at T=300K.

Problem 12
Schematic representations of the energy levels of a metal and an n-doped semiconductor are showed in the figure. The work functions of metal and semiconductor are given by 5.0 and 3.9 eV; respectively. The energy gap of the semiconductor is 1.4 eV, and the electron affinity is 3.2 eV. When the metal and semiconductor are contacted a Schottky junction forms.
The barrier height at the junction becomes: V_b = 5.0 - 3.2 = 1.8 eV

Problem 13

Soft ferromagnetic materials may be used for: transformers, flux guides and magnetic shielding.

Problem 14

Kerr effect in Si. The impermeability tensor becomes:

$$\eta_{ij}(E) = \eta^0_{ij} + \sum_{kl} s_{ijkl}E_kE_l \qquad and \qquad \eta^0_{11} = \eta^0_{22} = \eta^0_{33} = \frac{1}{n^2} \qquad others = 0$$

Only non-zero elements of the fourth rank tensor are (using contracted notation):

$$s_{11} = s_{22} = s_{33} \qquad s_{12} = s_{13} = s_{23} \qquad s_{44} = s_{55} = s_{66}$$

We get when the electric field is in the z-direction:

$$\sum_{ii} \eta_{ij}(E)x_ix_j = 1 \Rightarrow x^2\left(\frac{1}{n^2} + s_{1133}E^2\right) + y^2\left(\frac{1}{n^2} + s_{2233}E^2\right) + z^2\left(\frac{1}{n^2} + s_{3333}E^2\right) = 1$$

and further on:

$$\frac{1}{n^2} + s_{12}E^2 = \left(\frac{n^2}{1 + s_{12}E^2n^2}\right)^{-1} = \left(\frac{n^2}{\sqrt{1 + s_{12}E^2n^2}^2}\right)^{-1} = \left[n\left(n - \frac{1}{2}s_{12}E^2n^2\right)\right]^{-2}$$

using

$$\frac{1}{\sqrt{1+x}} \approx 1 - \frac{1}{2}x + \ldots \Rightarrow \Delta n = n_e - n_o = \frac{1}{2}E^2n^3(s_{12} - s_{11})$$

Problem 15

The piezoelectric tensor of a trigonal material of point group 32 is given by:

$$d = \begin{bmatrix} 0 & 0 & 0 & 0 & 735 & 0 \\ 0 & 0 & 0 & 735 & 0 & 0 \\ -263 & -263 & 515 & 0 & 0 & 0 \end{bmatrix}$$

in units of 10^{-12} C/N.

The polarization along the the x-axis for shear stress $\sigma = 10^4$ Nm^{-2} around the x-axis:

$P1 = d_{12}\,\sigma = 0$

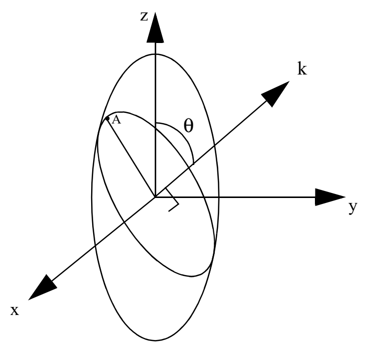
The polarization along the the x-axis for shear stress $\sigma = 10^4$ Nm^{-2} around the y-axis:

$P1 = d_{15}\,\sigma = 7.35\ 10^{-6}$ Cm^{-2}

The polarization along the the z-axis for normal stress $\sigma = 10^4$ Nm^{-2} along the y-axis:

$P3 = d_{32}\,\sigma = -2.63\ 10^{-6}$ Cm^{-2}

Problem 16



A uniaxial optical active material has index ellipsoid as shown above. The propagation direction of light is perpendicular to the ellipse shown in the figure, and the wave vector k is in the yz-plane. The point A is located on the ellipsoid and the ellipse in the yz-plane. The angle $\theta=55^o$ and the ordinary and extraordinary indices of refraction are n_{ro} =1.85 and n_{re} =1.65. What is the the refractive index $n_{re}(\theta)$ for light traveling in the k-direction?

From figure: $x_A = 0$, $y_A = |A|\cos\theta$, $z_A = |A|\sin\theta$

From ellipse: $|A| = n_{re}(\theta)$

The point A is on the index ellipsoid:

$$\frac{x_A^2}{n_{ro}} + \frac{y_A^2}{n_{ro}} + \frac{z_A^2}{n_{re}} = 1 \Rightarrow \frac{n_{re}(\theta)\cdot(\cos\theta)^2}{n_{ro}^2} + \frac{n_{re}(\theta)\cdot(\sin\theta)^2}{n_{re}^2} = 1$$

and we get:

$$\frac{1}{n_{re}(\theta)^2} = \frac{(\cos\theta)^2}{n_{ro}^2} + \frac{(\sin\theta)^2}{n_{re}^2}$$

Inserting numbers gives: $n_{re}(\theta=55^o) = 1.71$

Problem 17

Consider a Si pn-diode that is used as a solar cell. The temperature is 300 K. The total current of the diode connected to an external load is given by I where I_L is the photocurrent and I_0 is the diffusion current of electrons and holes. Find the open circuit voltage for the solar cell.

$$I = I_L - I_0(e^{eV/k_BT} - 1)$$

Diffusion currents for electrons on the p-side and holdes on the n-side is:

$$J_n = eD_n\frac{dn}{dx} = eD_n\cdot\frac{n_p}{L_n} \qquad and \qquad J_p = eD_p\frac{dp}{dx} = eD_n\cdot\frac{p_n}{L_p}$$

Using law of mass action:

$$n_pp_p = n_i^2 = n_np_n$$

Therefore:

$$\frac{I_0}{A} = eD_n\cdot\frac{n_p}{L_n} + eD_n\cdot\frac{p_n}{L_p} \quad where \quad L_n = \sqrt{D_n\tau_n} \quad and \quad L_p = \sqrt{D_p\tau_p}$$

The open circuit voltage becomes (I =0):

$$V_{OC} = \frac{k_BT}{e}\ln\left(1 + \frac{I_L}{I_0}\right) = 0{,}97V$$