ELEC-3140 Semiconductor physics **Mid-term exam 1, Oct 26, 2016**

Write your name, student number, degree programme (*e.g.*, NanoRad), course code, and date of the exam on each of the answer papers.

1. Explain briefly and exactly (with a couple of sentences):
   a) reciprocal lattice,
   b) zinc-blende lattice structure,
   c) dispersion relation,
   d) type I band alignment,
   e) vacancy,
   f) modulation doping.

2. a) Describe the division of crystal defects by their dimensionality. Give examples of crystal defects in each category. b) Describe the quantum structures by dimensionality. Also sketch the density of states (DOS) function for each one of them along with the bulk DOS. Place all the DOS functions in the same graph and be careful where you start each of the curves on the energy scale.

3. a) Describe how to determine the Miller indices for a crystal plane and for a crystal surface in a cubic crystal. b) Describe the main epitaxial growth methods and their operation principles. Compare the advantages and disadvantages of these methods.

4. a) Pseudomorphic $Ga_{0.4}In_{0.6}As$ layer has been grown epitaxially on an InP substrate. Calculate the relative lattice mismatch and the vertical component of the lattice constant of the layer on the InP substrate. b) Calculate the energy band gap of the layer material without the strain effects. c) Calculate the real energy band gap value with the strain effects included.

5. A hypothetical semiconductor has a density of states function approximated by

$$N(E) \propto C \cdot \sqrt{E - E_C}^{-3/2},$$

where C is an arbitrary constant. Calculate the energy at which the electron occupation has its maximum in a non-degerate (not highly doped) semiconductor crystal. You can use the Maxwell-Boltzmann distribution.

Constants:

$m_e = 9,1091 \times 10^{-31}$ kg	$m_p = 1,6725 \times 10^{-27}$ kg	$m_n = 1,6748 \times 10^{-27}$ kg	$\text{amu} = 1,6605 \times 10^{-27}$ kg
$e = 1,6021 \times 10^{-19}$ C	$c = 2,9979 \times 10^{8}$ m/s	$\hbar = 1,0545 \times 10^{-34}$ Js	$\mu_B = 9,2732 \times 10^{-24}\,\text{JT}^{-1}$
$\varepsilon_0 = 8,8544 \times 10^{-12}\,\text{C}^2\text{N}^{-1}\text{m}^{-2}$	$K_e = 1 / 4\pi\varepsilon_0$	$\mu_0 = 1,2566 \times 10^{-6}\,\text{mkgC}^{-2}$	$K_m = \mu_0 / 4\pi$
$\gamma = 6,670 \times 10^{-11}\,\text{Nm}^2\text{kg}^{-2}$	$N_A = 6,0225 \times 10^{23}\,\text{mol}^{-1}$	$R = 8,3143\,\text{JK}^{-1}\text{mol}^{-1}$	$k = 1,3805 \times 10^{-23}\,\text{JK}^{-1}$

TABLE 5.2-2 Energy Gaps of the Binary III–V Compounds

Compound	Type of energy gap	Experimental energy gap, E_g (eV) 0°K	Ref.	300°K	Ref.	Temperature dependence of energy gap, $E_g(T)$ (eV)
AlP	indirect	2.52	a	2.45	a	$2.52-3.18\times10^{-4}T^2/(T+588)^r$
AlAs	indirect	2.239	b	2.163	b	$2.239-6.0\times10^{-4}T^2/(T+408)^r$
AlSb	indirect	1.687	c	1.58	d	$1.687-4.97\times10^{-4}T^2/(T+213)$
GaP	indirect	2.338	e	2.261	e	$2.338-5.771\times10^{-4}T^2/(T+372)$
GaAs	direct	1.519	f	1.424	g	$1.519-5.405\times10^{-4}T^2/(T+204)$
GaSb	direct	0.810	h	0.726	i	$0.810-3.78\times10^{-4}T^2/(T+94)^r$
InP	direct	1.421	j	1.351	j	$1.421-3.63\times10^{-4}T^2/(T+162)^r$
InAs	direct	0.420	k	0.360	l	$0.420-2.50\times10^{-4}T^2/(T+75)^r$
InSb	direct	0.236	m	0.172	l	$0.236-2.99\times10^{-4}T^2/(T+140)^r$

TABLE 5.2-3 Selected Properties of III–V Binary Compounds

Compound	Electron affinity χ (eV)	Ref.	Conduction band effective mass m_n	Ref.	Valence band effective mass m_p	Ref.	Dielectric constant ε	Ref.	Refractive index at E_g, $\bar{n}$	Ref.	Thermal conductivity σ (W/cm-deg)	Ref.
AlP	—	—	—	—	$0.70m_0$	f	—	—	3.027	y	0.9	ff
AlAs	—	—	$0.15m_0$	g	$0.79m_0$	f	$10.1\varepsilon_0$	q	3.178	q	0.91	gg
AlSb	3.64	a	$0.12m_0$	h	$0.98m_0$	f	$14.4\varepsilon_0$	r	>3.4	z	0.57	ff
GaP	4.0^{est}	b	$0.82m_0$	i	$0.60m_0$	j	$11.1\varepsilon_0$	s	3.452	aa	0.77	ff
GaAs	4.05	c	$0.067m_0$	k	$0.48m_0$	k	$13.1\varepsilon_0$	t	3.655	bb	0.44	ff
GaSb	4.03	c	$0.042m_0$	h	$0.44m_0$	l	$15.7\varepsilon_0$	u	3.82	cc	0.33	ff
InP	4.4	d	$0.077m_0$	m	$0.64m_0$	n	$12.4\varepsilon_0$	v	3.450	dd	0.68	ff
InAs	4.54	e	$0.023m_0$	m	$0.40m_0$	o	$14.6\varepsilon_0$	w	~3.52	w	0.27	ff
InSb	4.59	c	$0.0145m_0$	p	$0.40m_0$	p	$17.7\varepsilon_0$	x	~4.0	ee	0.17	ff

Table 1. Material parameters for various zincblende-type semiconductors. Lattice constant a (in Å) at room temperature and elastic constants c_{11}, c_{12} and c_{44} (in 10^{12} dyn cm^{-2}; [15]). Valence-band average $E_{v,av}$ and hydrostatic deformation potentials a_v and $a_c(\Gamma)$ as calculated within Van de Walle's model-solid approach (in eV; [5]). Spin-orbit splittings Δ_0, band gaps $E_g(\Gamma)$, $E_g(X)$, $E_g(L)$ (at room temperature) and shear deformation potentials b and d (in eV; [16] and [22], except where indicated).

	a	c_{11}	c_{12}	c_{44}	$E_{v,av}$	Δ_0	$E_g(\Gamma)$	$E_g(X)$	$E_g(L)$	a_v	$a_c(\Gamma)$	b	d
AlP	5.451	1.32	0.63	0.62	−8.09	0.07[a]	3.58	2.45	3.11[c]	3.15	−5.54	−1.6[a]	
AlAs	5.660	1.25	0.53	0.54	−7.49	0.28	2.95	2.16[b]	2.60[c]	2.47	−5.64	−1.5[a]	
AlSb	6.136	0.88	0.43	0.41	−6.66	0.65	2.22	1.61[c]	2.21[c]	1.36	−6.97	−1.4	−4.3
GaP	5.451	1.41	0.62	0.70	−7.40	0.08	2.74	2.26	2.63	1.70	−7.14	−1.5	−4.6
GaAs	5.653	1.18	0.54	0.59	−6.92	0.34	1.42	1.91[b]	1.73[b]	1.16	−7.17	−1.7	−4.6
GaSb	6.096	0.88	0.40	0.43	−6.25	0.82	0.72	1.05[c]	0.76[c]	0.79	−6.85	−2.0	−4.8
InP	5.869	1.02	0.58	0.46	−7.04	0.11	1.35	2.21[d]	2.05[d]	1.27	−5.04	−1.6	−4.2
InAs	6.058	0.83	0.45	0.40	−6.67	0.38	0.36	1.37[d]	1.07[d]	1.00	−5.08	−1.8	−3.6
InSb	6.479	0.66	0.36	0.30	−6.09	0.81	0.17	1.63[d]	0.93[d]	0.36	−6.17	−2.1	−5.0

[a] Present work [16].
[b] [17].
[c] [21].
[d] [10].

Table 2. Band gap (at Γ) and spin–orbit splitting bowing parameters.

	$C(E_g)$	$C(\Delta_0)$	Reference
$AlAs_xSb_{1-x}$	0.84	0.15	[18]
$Al_xGa_{1-x}P$	0.0	0.0	[20]
$Al_xGa_{1-x}As$	0.37	0.0	[17, 27]
$Al_xGa_{1-x}Sb$	0.47	0.30	[21]
$Al_xIn_{1-x}P$	0.0	0.0	[22, 18]
$Al_xIn_{1-x}As$	0.70	0.15	[22, 18]
GaP_xAs_{1-x}	0.21	0.0	[22]
$GaAs_xSb_{1-x}$	1.2	0.60	[22, 18]
$Ga_xIn_{1-x}P$	0.79	0.0	[22, 28]
$Ga_xIn_{1-x}As$	0.36	0.15	[23, 29]
$Ga_xIn_{1-x}Sb$	0.42	0.0	[22]
InP_xAs_{1-x}	0.28	0.10	[24, 18]
InP_xSb_{1-x}	1.3	0.75	[25, 18]
$InAs_xSb_{1-x}$	0.58	1.2	[22, 29]