NAME ____TEST 1 KEY_______________________________________

1. (5 easy points to start you off)

Elemental semiconductors occupy group _______IV_______ of the periodic table.

2. (10 points) For a body centered cubic lattice of identical atoms with a lattice constant of 7Å, calculate the radius of the atoms treated as hard spheres with nearest neighbors touching and the maximum packing fraction for the unit cell.

BCC has 2 atoms per cube. Two atomic diameters span each body diagonal, thus the nearest neighbor atoms will be $1/2\sqrt{3a^2} = 1/2 * a\sqrt{3} = 6.06$ angstroms distant, making the atomic radius = $3.03*10^{-10}$ *m.* Using this as r in (4/3)πr^3 times two atoms, and dividing that by a^3 yields a packing factor of 68%

3. (10 points) Using Appendix III, fill in the table below, with λ being the wavelength of light that would be emitted at the energy of the corresponding band gap. Show your calculation including units for at least one case directly below the table.

[HINT: Remember that band gap is given in eV should you need to select a constant to use anywhere in this calculation.]

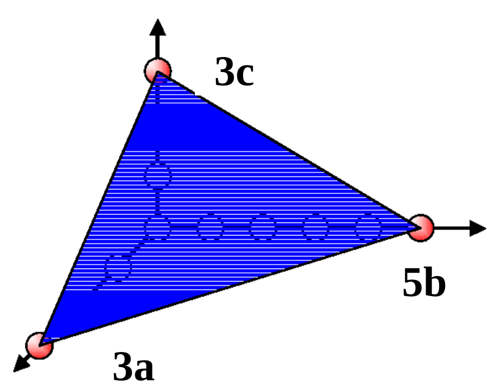
Semiconductor	Band Gap	λ (μm)
Silicon	1.1	1.12
Germanium	0.67	1.85
Silicon Carbide	2.86	0.434
Gallium Arsenide	1.43	0.867
Gallium Nitride	3.4	0.365

Two steps get you from Band Gap (energy) to wavelength. First you calculate the frequency that corresponds to each band gap using $v = E/h$ and then calculate the answer for that band gap using $\lambda = c/v$.

$\lambda = c/v$ is used whenever photos are involved. The question asked for light wavelength, not particle (i.e. electron) wavelength, which would use $\lambda = h/p$.

4. (10 points) Compute and properly denote the Miller Indices of the crystal plane shown below.

abc = 353
Inverted = 1/3, 1/5, 1/3
Normalized (15 is the LCD) = 5,3,5
Properly denoted as a Miller Index = (535)



5. (10 points) How many grams of Phosphorous (atomic weight of 31) are needed to dope 5*kg* of Si to $10^{17}/cm^3$, given a distribution coefficient, k_d, of 0.25?

The initial atomic concentration of phosphorous should be the desired doping adjusted by the diffusion constant, or $10^{17}/0.25 = 4 * 10^{17}$ atoms/ cm^3
$5000g/2.33g/cm^3$ (the density of Si) = 2146 cm^3 of Si
2146 cm^3 of Si requires $4 * 10^{17} * 2146 = 8.58 * 10^{20}$ phosphorous atoms
or in grams, ($8.58*10^{20}$ atoms * 31 grams/mole of phosphorous)/$6.02*10^{23}$ atoms per mole which equals $44.2 * 10^{-3}$ grams of phosphorous

6. (10 points) Calculate the densities (grams/cubic centimeter) of Silicon and Gallium Arsenide. The atomic weights of Si, Ga and As are 28.1, 69.7 and 74.9 respectively. [Hint: Both are diamond lattice with 8 equivalent atoms per unit cell. Thus the GaAs unit cell will contain 4 atoms of each species. Lattice information is in Appendix III]

Si: a = 5.43Å, 8 atoms per unit cell → $8/(5.43*10^{-8})^3 = 5*10^{22}$ *atoms* per cm^3

$(5*10^{22}*28.1)/6.02*10^{23}$ = 2.33 grams/cm^3

GaAs: a = 5.65Å, 4 atoms each of Ga and of As per unit cell → $4/(5.65*10^{-8})^3 = 2.22*10^{22}$ *molecules* per cm

$(2.22*10^{22}*(69.7+74.9)/6.02*10^{23}$ = 5.33 grams/cm^3

7. (10 points) Calculate the velocity of an electron with 4 *eV* of kinetic energy.

From E = ½ mv^2, $v = \sqrt{\frac{2E}{m}} = \sqrt{\frac{8*1.6*10^{-19}}{9.11*10^{-31}}} = 1.19*10^6$ *m/s*

8. (5 points) Bohr's model of the Hydrogen atom gives the potential energy of the electron as $E = -13.56\ eV/n^2$, where *n* is the quantum (orbit) number.

What is the potential energy of the outermost electron in potassium which has the electron configuration $K = 1s^2 2s^2 2p^6 3s^2 3p^6 4s^1$?

$E = -13.56\ eV/n^2$ where n=4, E = -0.8475 *eV*

9. (5 points) Calculate the minimum uncertainty of momentum for a particle whose position is known to within 3.0*Å*.

$$\Delta p \Delta x \geq \frac{\hbar}{2} \qquad \Delta p \geq \frac{\hbar/2}{\Delta x} = \frac{h}{4\pi \Delta x} = \frac{6.63*10^{-34}(kgm^2/s^{2})}{4\pi*3.0*10^{-10}(m)} = 1.76*10^{-25}\ \text{kg}\cdot\text{m/s}$$

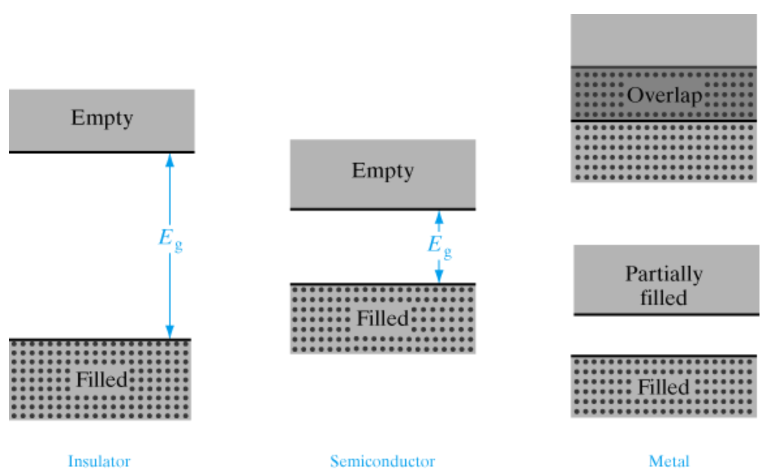
10. (5 points) Calculate the minimum uncertainty of time for a particle whose energy is known to within 2 *eV*.

$$\Delta t \Delta E \geq \frac{\hbar}{2} \qquad \Delta t \geq \frac{\hbar/2}{\Delta p} = \frac{h}{4\pi \Delta p} = \frac{4.14*10^{-15} eVs}{4\pi*2eV} = 1.65*10^{-16}\ \text{s}$$

<u>True/False – Circle the correct answer, T for true, or F for false, for 1 point each. Understand that the statement must be 100% true to be correctly considered as true.</u>

11. T F Schrodinger's study of wave mechanics was independent of work conducted by Heisenberg.
12. T F *Pauli's exclusion* principle states that no two interacting electrons can have the same quantum numbers.
13. T F Intrinsic silicon has approximately $1.5*10^{10}$ EHPs at 300*K*.
14. T F There are no electron-hole pairs (EHPs) in intrinsic crystalline silicon at 0*K*.
15. T F Essentially all donor atoms are thermally ionized at 100*K*.

16. (5 points) Draw three energy band diagrams that illustrate the difference between, conductors, semiconductors and insulators.



17. (1 point each) Match each term or phrase in the list below to its correct description by indicating the letter of the description in the term/phrase's box.

Boule	n
Doping	a
Diffusion	i
Die	j
Lead Frame	e
Ion Implantation	o
Wire Bond	m
Photoresist	c
Vias	b
Burn-in	f

a.	the process of intentionally introducing impurities into an extremely pure (also referred to as *intrinsic*) semiconductor in order to change its electrical properties
b.	conducting pathways cut through insulating layers of an integrated circuit or printed wiring board device.
c.	an ultraviolet light sensitive organic material or photo emulsion dispensed as a liquid onto the wafer surface to allow an image to be exposed and developed on the wafer.
d.	a widely used method of encapsulating semiconductor devices after they are electrically connected to a lead frame.
e.	a finely patterned metal structure onto which a die is mounted and/or is electrically connected.
f.	a post-packaging process wherein numerous devices are operated at high temperature to encourage early failure of "weak" parts.
g.	the material upon which semiconductor devices are fabricated.
h.	a method of soldering device leads to the surface of a printed wiring board.
i.	a high-temperature process of introducing dopant atoms into a semiconductor crystal lattice during which dopant atoms (impurities) distribute themselves in accordance with the second law of thermodynamics.
j.	a rectangular chip inscribed from a wafer that contains one integrated circuit.
k.	a computer driven test of packaged devices to insure functionality and to sort devices into groups with respect to performance.
l.	a photographic method of pattern definition employing ultraviolet radiation to form complex circuitry on a semiconductor wafer.
m.	fine gold and aluminum wire used to electrically connect an integrated circuit/semiconductor device to a lead frame or any other next level of interconnection.
n.	a single crystal ingot produced by synthetic means.
o.	the most common technique of dopant introduction in advanced semiconductor manufacturing during which ions are accelerated toward solid surface and penetrate the solid up to certain depth determined by ion energy
p.	a method of soldering device leads into plated holes drilled through a printed wiring board.

Appendix III

Properties of Semiconductor Materials

		E_g (ev)	μ_n (cm²/V-s)	μ_p (cm²/V-s)	m^*_n/m_o (m_l, m_t)	m^*_p/m_o (m_{lh}, m_{hh})	a (Å)	ϵ_r	Density (g/cm³)	Melting point (°C)
Si	(*i*/*D*)	1.11	1350	480	0.98, 0.19	0.16, 0.49	5.43	11.8	2.33	1415
Ge	(*i*/*D*)	0.67	3900	1900	1.64, 0.082	0.04, 0.28	5.65	16	5.32	936
SiC (α)	(*i*/*W*)	2.86	500	—	0.6	1.0	3.08	10.2	3.21	2830
AlP	(*i*/*Z*)	2.45	80	—	—	0.2, 0.63	5.46	9.8	2.40	2000
AlAs	(*i*/*Z*)	2.16	1200	420	2.0	0.15, 0.76	5.66	10.9	3.60	1740
AlSb	(*i*/*Z*)	1.6	200	300	0.12	0.98	6.14	11	4.26	1080
GaP	(*i*/*Z*)	2.26	300	150	1.12, 0.22	0.14, 0.79	5.45	11.1	4.13	1467
GaAs	(*d*/*Z*)	1.43	8500	400	0.067	0.074, 0.50	5.65	13.2	5.31	1238
GaN	(*d*/*Z*, *W*)	3.4	380	—	0.19	0.60	4.5	12.2	6.1	2530
GaSb	(*d*/*Z*)	0.7	5000	1000	0.042	0.06, 0.23	6.09	15.7	5.61	712
InP	(*d*/*Z*)	1.35	4000	100	0.077	0.089, 0.85	5.87	12.4	4.79	1070
InAs	(*d*/*Z*)	0.36	22600	200	0.023	0.025, 0.41	6.06	14.6	5.67	943
InSb	(*d*/*Z*)	0.18	10^5	1700	0.014	0.015, 0.40	6.48	17.7	5.78	525
ZnS	(*d*/*Z*, *W*)	3.6	180	10	0.28	—	5.409	8.9	4.09	1650*
ZnSe	(*d*/*Z*)	2.7	600	28	0.14	0.60	5.671	9.2	5.65	1100*
ZnTe	(*d*/*Z*)	2.25	530	100	0.18	0.65	6.101	10.4	5.51	1238*
CdS	(*d*/*W*, *Z*)	2.42	250	15	0.21	0.80	4.137	8.9	4.82	1475
CdSe	(*d*/*W*)	1.73	800	—	0.13	0.45	4.30	10.2	5.81	1258
CdTe	(*d*/*Z*)	1.58	1050	100	0.10	0.37	6.482	10.2	6.20	1098
PbS	(*i*/*H*)	0.37	575	200	0.22	0.29	5.936	17.0	7.6	1119
PbSe	(*i*/*H*)	0.27	1500	1500	—	—	6.147	23.6	8.73	1081
PbTe	(*i*/*H*)	0.29	6000	4000	0.17	0.20	6.452	30	8.16	925

All values at 300 K. *Vaporizes

The first column lists the semiconductor, the second indicates band structure type and crystal structure. Definitions of symbols: *i* is indirect; *d* is direct; *D* is diamond; *Z* is zincblende; *W* is wurtzite; *H* is halite (NaCl). Values of mobility are for material of high purity.

Crystals in the wurtzite structure are not described completely by the single lattice constant given here, since the unit cell is not cubic. Several II–VI compounds can be grown in either the zincblende or wurtzite structures.

Many values quoted here are approximate or uncertain, particularly for the II–VI and IV–VI compounds. The gaps indicate that the values are unknown.

For electrons, the first set of band curvature effective masses is the longitudinal mass, the second set the transverse. For holes, the first set is for light holes, the second for heavy holes.

Appendix II

Physical Constants and Conversion Factors[1]

Avogadro's number	$N_A = 6.02 \times 10^{23}$ molecules/mole
Boltzmann's constant	$k = 1.38 \times 10^{-23}$ J/K
	$= 8.62 \times 10^{-5}$ eV/K
Electronic charge (magnitude)	$q = 1.60 \times 10^{-19}$ C
Electronic rest mass	$m_0 = 9.11 \times 10^{-31}$ kg
Permittivity of free space	$\epsilon_0 = 8.85 \times 10^{-14}$ F/cm
	$= 8.85 \times 10^{-12}$ F/m
Planck's constant	$h = 6.63 \times 10^{-34}$ J-s
	$= 4.14 \times 10^{-15}$ eV-s
Room temperature value of kT	$kT = 0.0259$ eV
Speed of light	$c = 2.998 \times 10^{10}$ cm/s

	Prefixes:		
1 Å (angstrom) $= 10^{-8}$ cm	milli-,	m-	$= 10^{-3}$
1 μm (micron) $= 10^{-4}$ cm	micro-,	μ-	$= 10^{-6}$
1 nm = 10Å $= 10^{-7}$ cm	nano-,	n-	$= 10^{-9}$
2.54 cm = 1 in.	pico-,	p-	$= 10^{-12}$
1 eV $= 1.6 \times 10^{-19}$ J	kilo-,	k-	$= 10^{3}$
	mega-,	M-	$= 10^{6}$
	giga-,	G-	$= 10^{9}$

A wavelength λ of 1 μm corresponds to a photon energy of 1.24 eV.

[1]Since cm is used as the unit of length for many semiconductor quantities, caution must be exercised to avoid unit errors in calculations. When using quantities involving length in formulas which contain quantities measured in MKS units, it is usually best to use all MKS quantities. Conversion to standard semiconductor usage involving cm can be accomplished as a last step. Similar caution is recommended in using J and eV as energy units.

SEMICONDUCTOR PHYSICS

Electron Momentum: $\mathsf{p} = m\mathsf{v} = \hbar\mathbf{k} = \dfrac{h}{\lambda}$ Planck: $E = h\nu = \hbar\omega$

Kinetic: $E = \dfrac{1}{2}m\mathsf{v}^2 = \dfrac{1}{2}\dfrac{\mathsf{p}^2}{m} = \dfrac{\hbar^2}{2m^*}\mathbf{k}^2$ (3–4) Effective mass: $m^* = \dfrac{\hbar^2}{d^2E/d\mathbf{k}^2}$ (3–3)

Total electron energy $= P.E. + K.E. = E_c + E(\mathbf{k})$

Fermi-Dirac e^- distribution: $f(E) = \dfrac{1}{e^{(E-E_F)/kT} + 1} \cong e^{(E_F-E)/kT}$ for $E \gg E_F$ (3–10)

Equilibrium: $n_0 = \displaystyle\int_{E_c}^{\infty} f(E)N(E)dE = N_c f(E_c) = N_c e^{-(E_c-E_F)/kT}$ (3–15)

$N_c = 2\left(\dfrac{2\pi m_n^* kT}{h^2}\right)^{3/2}$ $N_v = 2\left(\dfrac{2\pi m_p^* kT}{h^2}\right)^{3/2}$ (3–16), (3–20)

$p_0 = N_v[1 - f(E_v)] = N_v e^{-(E_F-E_v)/kT}$ (3–19)

$n_i = N_c e^{-(E_c-E_i)/kT}$, $p_i = N_v e^{-(E_i-E_v)/kT}$ (3–21)

$n_i = \sqrt{N_c N_v}\, e^{-E_g/2kT} = 2\left(\dfrac{2\pi kT}{h^2}\right)^{3/2}(m_n^* m_p^*)^{3/4} e^{-E_g/2kT}$ (3–23), (3–26)

Equilibrium: $\begin{aligned} n_0 &= n_i e^{(E_F-E_i)/kT} \\ p_0 &= n_i e^{(E_i-E_F)/kT} \end{aligned}$ (3–25) $n_0 p_0 = n_i^2$ (3–24)

Steady state: $\begin{aligned} n &= N_c e^{-(E_c-F_n)/kT} = n_i e^{(F_n-E_i)/kT} \\ p &= N_v e^{-(F_p-E_v)/kT} = n_i e^{(E_i-F_p)/kT} \end{aligned}$ (4–15) $np = n_i^2 e^{(F_n-F_p)/kT}$ (5–38)

$\mathscr{E}(x) = -\dfrac{d\mathscr{V}(x)}{dx} = \dfrac{1}{q}\dfrac{dE_i}{dx}$ (4–26)

Poisson: $\dfrac{d\mathscr{E}(x)}{dx} = -\dfrac{d^2\mathscr{V}(x)}{dx^2} = \dfrac{\rho(x)}{\epsilon} = \dfrac{q}{\epsilon}(p - n + N_d^+ - N_a^-)$ (5–14)

$\mu \equiv \dfrac{q\bar{t}}{m^*}$ (3–40a) Drift: $\mathsf{v}_d \cong \dfrac{\mu\mathscr{E}}{1 + \mu\mathscr{E}/\mathsf{v}_s}\begin{cases} = \mu\mathscr{E} \text{ (low fields, ohmic)} \\ = \mathsf{v}_s \text{ (high fields, saturated vel.)} \end{cases}$ (Fig. 6–9)

Drift current density: $\dfrac{I_x}{A} = J_x = q(n\mu_n + p\mu_p)\mathscr{E}_x = \sigma\mathscr{E}_x$ (3–43)

Conduction Current:

$$J_n(x) = q\mu_n n(x)\mathscr{E}(x) + qD_n\frac{dn(x)}{dx}$$

drift diffusion (4–23)

$$J_p(x) = q\mu_p p(x)\mathscr{E}(x) - qD_p\frac{dp(x)}{dx}$$

$J_{\text{total}} = J_{\text{conduction}} + J_{\text{displacement}} = J_n + J_p + C\dfrac{dV}{dt}$

Continuity: $\dfrac{\partial p(x,t)}{\partial t} = \dfrac{\partial \delta p}{\partial t} = -\dfrac{1}{q}\dfrac{\partial J_p}{\partial x} - \dfrac{\delta p}{\tau_p}$ $\dfrac{\partial \delta n}{\partial t} = \dfrac{1}{q}\dfrac{\partial J_n}{\partial x} - \dfrac{\delta n}{\tau_n}$ (4–31)

For steady state diffusion: $\dfrac{d^2\delta n}{dx^2} = \dfrac{\delta n}{D_n\tau_n} \equiv \dfrac{\delta n}{L_n^2}$ $\dfrac{d^2\delta p}{dx^2} = \dfrac{\delta p}{L_p^2}$ (4–34)

Diffusion length: $L \equiv \sqrt{D\tau}$ Einstein relation: $\dfrac{D}{\mu} = \dfrac{kT}{q}$ (4–29)