University of Texas Arlington
Department of Electrical Engineering

Nanotechnology – Microelectromechanical Systems
Ph.D. Diagnostic Examination

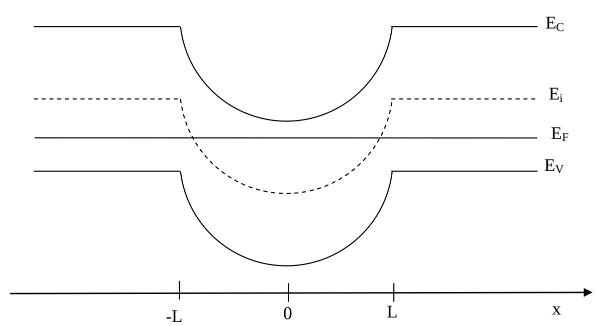
SPRING 2009 – April 25, 2009

	To be filled by the student	***To be filled by the graders***		
Question #	**Check to have this question graded. Check only 2.**	**Grade**	**Grade**	**Average**
1				
2				
3				
			TOTAL:	
			GRADE OUT of 100:	

THIS EXAM PACKET HAS **8** SHEETS INCLUDING THE HELPFUL EQUATIONS AND CONSTANTS.

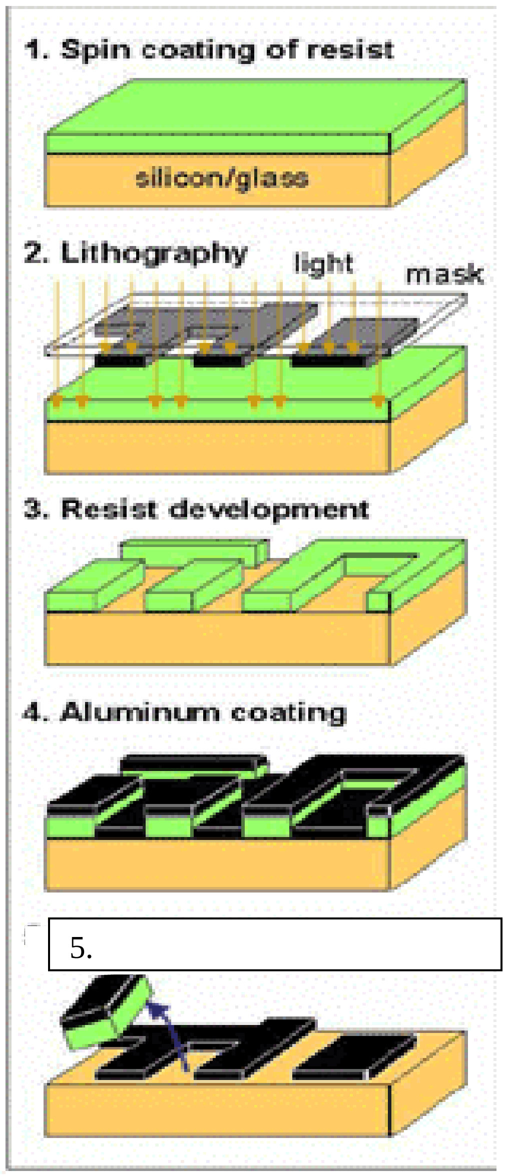
1. (50pt) The energy band diagram pictured in the Figure below characterizes a Si sample maintained at room temperature. Note that E_i-E_F=E_G/4 at x=L and x=-L. E_F-E_i=E_G/4 at x=0.
   a. (5pt) The semiconductor is in equilibrium. How does one deduce this fact from the given energy band diagram?
   b. (5pt) What is the electron current density (J_N) and hole current density (J_P) at x=+L/2 and x=-L/2?
   c. (5pt) Roughly sketch n and p versus x inside the sample
   d. (10pt) Is there an *electron* diffusion current at x=+L/2 and x=-L/2? If there is a diffusion current at a given point, indicate the direction of the current flow.
   e. (15pt) Sketch the electrostatic potential, electric field, and charge density inside the semiconductor as a function of x
   f. (10 pt) Is there an *electron* drift current at x=+L/2 and x=-L/2? If there is a drift current at a given point, indicate the direction of the current flow.

Assume that the function -L<x<L is quadratic: x^2



2. (50 pts) Si is doped with $N_D = 10^{16}$ cm^{-3} As atoms. (E_c-E_D=0.054 eV) Determine the fraction of the donors that are ionized and the location of the Fermi energy with respect to the conduction band at T=77 K given m_n*=1.062m_o, m_p*=0.590m_o, and E_G=1.12 eV.

3. Please refer to the schematic below.
   a. (20 pts) What CMOS/MEMS fabrication procedure do the schematics below represent (Be specific)? ______________________________
   b. (10 pts) Write the processing step for last line (#5) below.
   c. (20 pts) Is the photoresist positive or negative? Why?



Physical Constants
(in units frequently used in semiconductor electronics)

Electronic charge	q	1.602×10^{-19} C
Speed of light in vacuum	c	2.998×10^{10} cm s^{-1}
Permittivity of vacuum	ε_0	8.854×10^{-14} F cm^{-1}
Free electron mass	m_0	9.11×10^{-31} kg
Planck's constant	h	6.626×10^{-34} J s
		4.135×10^{-15} eV s
Boltzmann's constant	k	1.38×10^{-23} J K^{-1}
		8.62×10^{-5} eV K^{-1}
Avogadro's number	A_0	6.022×10^{23} molecules (g mole)$^{-1}$
Thermal voltage	$V_t=kT/q$	
at 80.6˚ F (300K)		2.586 mV
68˚ F (293K)		2.025 mV

Conversion Factors

1 Å = 10^{-8} cm = 0.1nm
1 mil = 10^{-3} inch = 25.4 μm
1 eV = 1.602×10^{-19} J
1 J = 10^{7} erg

Appendix III

Properties of Semiconductor Materials

		E_g (ev)	μ_n (cm^2/V-s)	μ_p (cm^2/V-s)	m^*_n/m_o (m_l, m_t)	m^*_p/m_o (m_{lh}, m_{hh})	a (Å)	ϵ_r	Density (g/cm^3)	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.

Useful Equations

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

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

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

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

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

$N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$ $N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$ (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)

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

Equilibrium: $n_0 = n_i e^{(E_F-E_i)/kT}$, $p_0 = n_i e^{(E_i-E_F)/kT}$ (3–25) $n_0 p_0 = n_i^2$ (3–24)

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

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

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

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

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

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

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

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

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

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