University of Texas Arlington
Department of Electrical Engineering

Nanotechnology – Microelectromechanical Systems
Ph.D. Diagnostic Examination

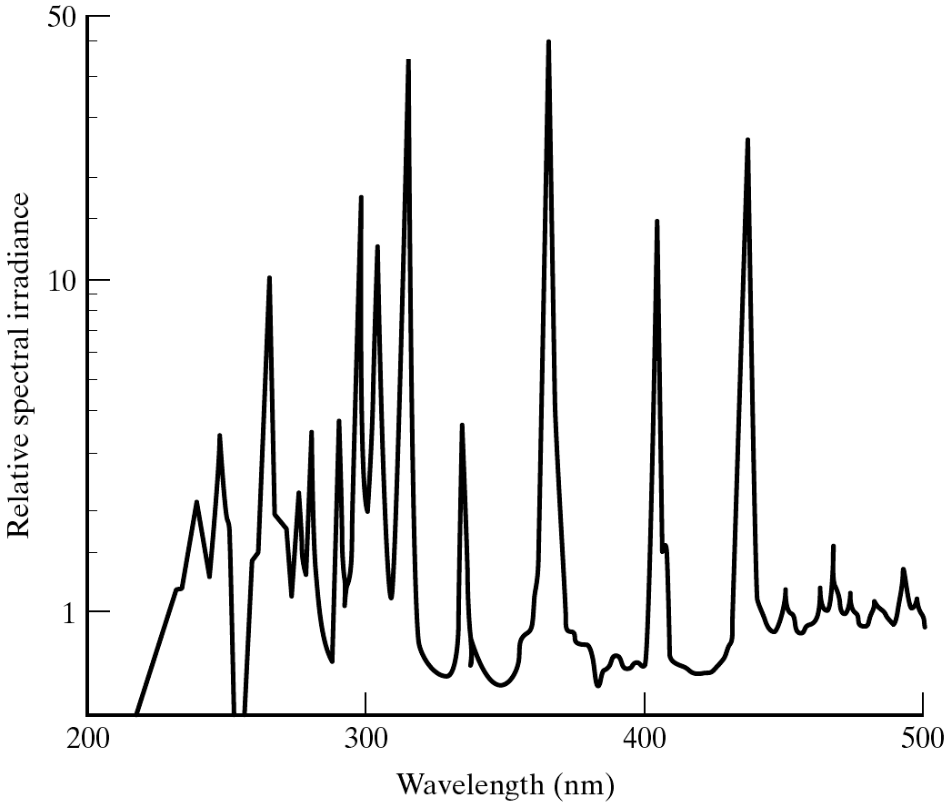
Fall 2011 – November 19, 2011

	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 **9** SHEETS INCLUDING THE HELPFUL EQUATIONS AND CONSTANTS.

1. (50 pts)

Following plot shows a typical spectral content of a lamp used for optical lithography.



(a) Identify the DUV and UV regions on the plot? (10 points)

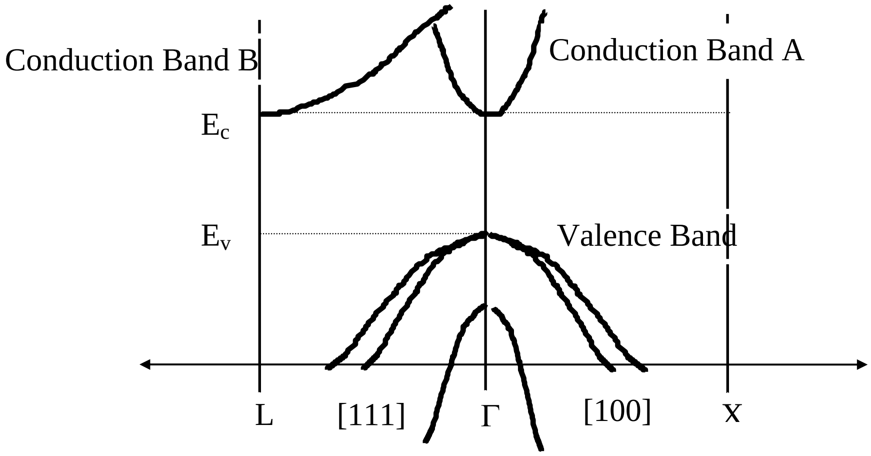
(b) What wavelength of the lamp output should be most suitable for the 250 nm technology and below? (10 points)

(c) Considering *NA* ≥ 0.5 and using phase-shifting mask, what minimum feature size can be achieved with the wavelength of question (b)? (15 points)

(d) What would be expected depth of field for this system? (15 points)

2. (50 points)

Congratulations, you have just discovered a new semiconductor, “utaium” which has a cubic crystal structure. The E-k relationship is shown in the figure below. The conduction bands “A” and “B” have the same energy minima E_c.



a) Draw the constant energy surface(s) for electrons near the conduction band minima in k-space.

b) Given the following inverse effective mass tensor data measured by cyclotron resonance at 4 K. Calculate the density of states effective mass for the conduction band, m_n^*.

Conduction Band A

$$\frac{m_o}{m^*} = \begin{bmatrix} 5 & 0 & 0 \\ 0 & 5 & 0 \\ 0 & 0 & 5 \end{bmatrix}$$

$m_o = 9.1 \times 10^{-31}$ kg

Conduction Band B

$$\frac{m_o}{m^*} = \begin{bmatrix} 0.05 & 0 & 0 \\ 0 & 0.2 & 0 \\ 0 & 0 & 0.2 \end{bmatrix}$$

c) Given the effective mass data for the valence bands are $m_{hh}=0.347m_o$, $m_{lh}=0.0429m_o$, and $m_{so}=0.077m_o$; determine the density of states effective mass for holes in the valence band m_p^*.

Assume parabolic constant energy surfaces at the band minima.

Note: The volume of a prolate spheroid is $\frac{4\pi ab^2}{3}$ where 2a and 2b are the lengths of the major and minor axes respectively of the rotated ellipse.

3. (50 pts)

Crystalline silicon has a lattice constant of 5.43095 Å and an atomic weight of 28.09 gm/mole.

a) What is the Bravais lattice of Si?

b) What is the crystal structure of Si?

c) What is the crystal system of Si?

d) What are the symmetry properties of Si?

e) How many atoms are there per unit cell?

f) What is the mass density of Si?

COLOR CHART FOR THERMALLY GROWN SiO$_2$ FILMS

(OBSERVED PERPENDICULARLY UNDER DAYLIGHT FLURORESCENT LIGHTING)

OXIDE Film Thickness (Microns)	NITRIDE Order (5450 A)	Color and Comments
0.050	375 A	Tan
0.075	562.5	Brown
0.100	750	Dark Violet to red violet
0.125	937.5	Royal blue
0.150	1125	Light blue to metallic blue
0.175	1312.5	Metallic to very light yellow-green .
0.200	1500	Light gold or yellow slightly metallic
0.225	1687.5	Gold with slight yellow-orange
0.250	1875	Orange to Melon
0.275	2062.5	Red-Violet .
0.300	2250	Blue to violet-blue
0.310	2325	Blue
0.325	2437.5	Blue to blue-green
0.345	2587.5	Light green
0.350	2625	Green to yellow-green
0.365	2737.5	Yellow-green
0.375	2812.5	Green- yellow
0.390	2925	Yellow .
0.412	3090	Light orange
0.426	3195	Carnation pink
0.443	3322.5	Violet-red
0.465	3487.5	Red-violet
0.476	3570	Violet
0.480	3600	Blue Violet
0.493	3697.5	Blue
0.502	3765	Blue-green
0.520	3900	Green (Broad)
0.540	4050	Yellow-green
0.560	4200	Green-yellow
0.574	4305	Yellow to "Yellowish (not yellow but is in the position where yellow is to be expected. At times is appears to be light creamy gray or metallic)
0.585	4357.5	Light orange or yellow to pink borderline
0.60	4500	Carnation pink
0.63	4725	Violet-red

OXIDE Film Thickness (Microns)	NITRIDE Order (5450 A)	
0.68	5100	"Bluish" (Not blue but borderline between violet and blue-green. It appears more like a Mixture between violet -red and blue-green and over-all looks grayish.
0.72	5400	Blue-green to green (quite broad
0.77	5775	"Yellowish"
0.80	6000	Orange (rather broad for orange)
0.82	6150	Salmon
0.85	6375	Dull, light red-violet
0.86	6490	Violet
0.87	6525	Blue-violet
0.89	6675	Blue
0.92	6900	Blue-green
0.95	7125	Dull yellow-green
0.97	7225	Yellow to Yellowish
0.99	7425	Orange
1.00	7500	Carnation Pink
1.02	7650	Violet-red
1.05	7575	Red-violet
1.06	7950	Violet
1.07	8025	Blue-violet
1.10	8250	Green
1.11	8325	Yellow-green
1.12	8400	Green
1.18	8850	Violet
1.19	8925	Red-violet
1.21	9075	Violet-red
1.24	9300	Carnation Pink-Salmon
1.25	9375	Orange
1.28	9600	"Yellowish"
1.32	9900	Sky blue to green-blue
1.40	10500	Orange
1.45	10875	Violet
1.45	10950	Blue-violet
1.50		Blue
1.51	11550	Dull Yellow-green

Physical Constants

(in units frequently used in semiconductor electronics)

Electronic charge	q	1.602 x 10^{-19} C
Speed of light in vacuum	c	2.998 x 10^{10} cm s^{-1}
Permittivity of vacuum	ε_0	8.854 x 10^{-14} F cm^{-1}
Free electron mass	m_0	9.11 x 10^{-31} kg
Planck's constant	h	6.626 x 10^{-34} J s 4.135 x 10^{-15} eV s
Boltzmann's constant	k	1.38 x 10^{-23} J K^{-1} 8.62 x 10^{-5} eV K^{-1}
Avogadro's number	A_0	6.022 x 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 x 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: $\mathrm{p} = m\mathrm{v} = \hbar\mathbf{k} = \dfrac{h}{\lambda}$ Planck: $E = h\nu = \hbar\omega$

Kinetic: $E = \dfrac{1}{2}m\mathrm{v}^2 = \dfrac{1}{2}\dfrac{\mathrm{p}^2}{m} = \dfrac{\hbar^2}{2m^*}\mathbf{k}^2$ (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)

$$N_D^+ = \frac{N_D}{1 + g_D exp\left(\frac{E_F - E_D}{k_B T}\right)}$$

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

$$N_A^- = \frac{N_A}{1 + g_A exp\left(\frac{E_A - E_F}{k_B T}\right)}$$

$n_i = N_c e^{-(E_c - E_i)/kT}$, $p_i = N_v e^{-(E_i - E_v)/kT}$ (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) $N_D^+ + p = N_A^- + n$

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: $\mathrm{v}_d \cong \dfrac{\mu\mathscr{E}}{1 + \mu\mathscr{E}/\mathrm{v}_s}\begin{cases} = \mu\mathscr{E} \text{ (low fields, ohmic)} \\ = \mathrm{v}_s \text{ (high fields, saturated vel.)} \end{cases}$ (Fig. 6–9)

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

Conduction Current:

$$J_n(x) = \underset{\text{drift}}{q\mu_n n(x)\mathscr{E}(x)} + \underset{\text{diffusion}}{qD_n\frac{dn(x)}{dx}} \qquad (4\text{–}23)$$

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

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

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

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

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

$$E\psi(r) = -\frac{\hbar^2}{2m}\nabla^2\psi(r) + V(r)\psi(r).$$