3.15 Electrical, Optical, and Magnetic Materials and Devices
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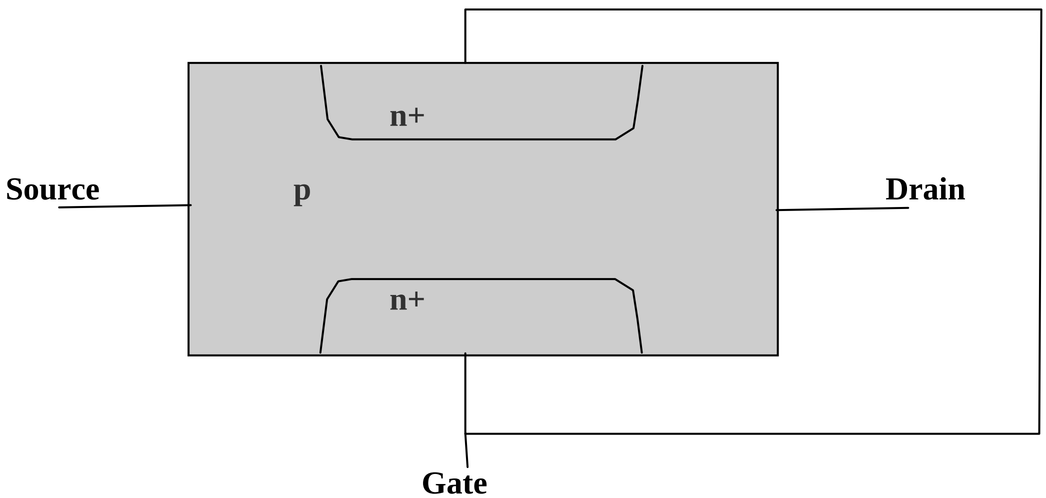
Exam 2 (6 pages)
Closed book exam. Formulae and data are on the last 4 pages of the exam.
This takes **80 min** and there are 80 points total. Be brief in your answers and use sketches.
Assume everything is at 300K unless otherwise noted.

1. [25 points] A JFET is constructed like this: the two gate regions are n+ and the rest of the material is p type.

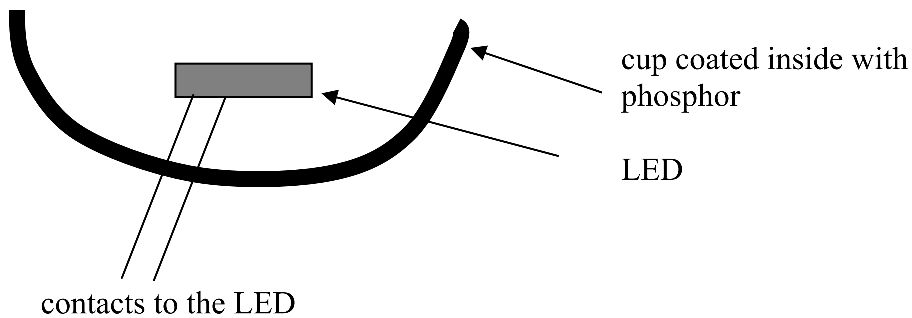


a) Assume that the source is grounded (at zero volts). Draw a sketch of how the current I_D flowing out of the drain varies with voltage V_D when the gate is at zero volts. Consider both positive and negative values of V_D and explain the shape of your graph. (3-4 sentences) [9]

b) Now draw another sketch showing again I_D vs. V_D but this time draw different graphs corresponding to different values of gate voltage V_G (both positive and negative). Explain briefly how gate voltage affects the I-V plot. [10]

c) Give three reasons why a MOSFET is preferable to a JFET. [6]

2. [33 points] In one of the problem sets we considered two ways of making white light using an LED. Here we will consider a third method. In this new scheme, the device looks like this:



a) What is the purpose of the phosphor-coated cup in this device? Explain how you can get white light. [6]

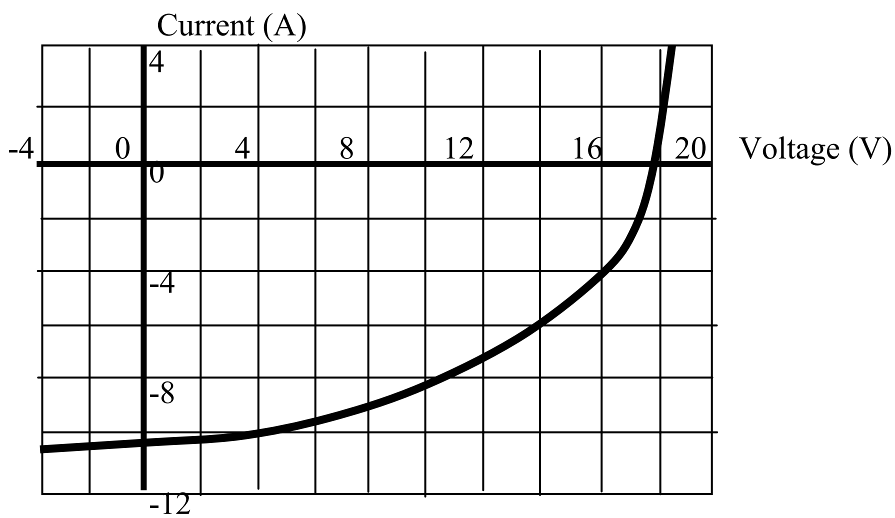
b) What color LED would you use? Choose a possible material and substrate for the LED, explaining your choice. [7] (some of the data at the end of the exam may be helpful)

c) Draw a possible band structure for your LED, in the unbiased case, and explain how bias affects the band structure. [7]

d) Explain concisely the differences between the spectral output of an LED, such as the one you just drew, compared with a semiconductor laser. [6]

e) If your LED is only 0.1 mm long, how does this affect its output? [7]

3. [22 points] We are designing a photovoltaic system. The solar cell we have available produces an output as shown below: its internal resistance is 0.2 ohms.



a) Estimate the maximum power we can produce from the solar cell. [6]

b) What load resistance would you use to maximize the output power? [4]

c) Mention three methods to improve the efficiency of a solar cell. (1 sentence each). [6]

d) Solar cells can be made from amorphous silicon, and are commonly used in devices such as calculators. Explain the reason for using amorphous Si in place of crystal Si (3-4 sentences). [6]

Data and Formulae

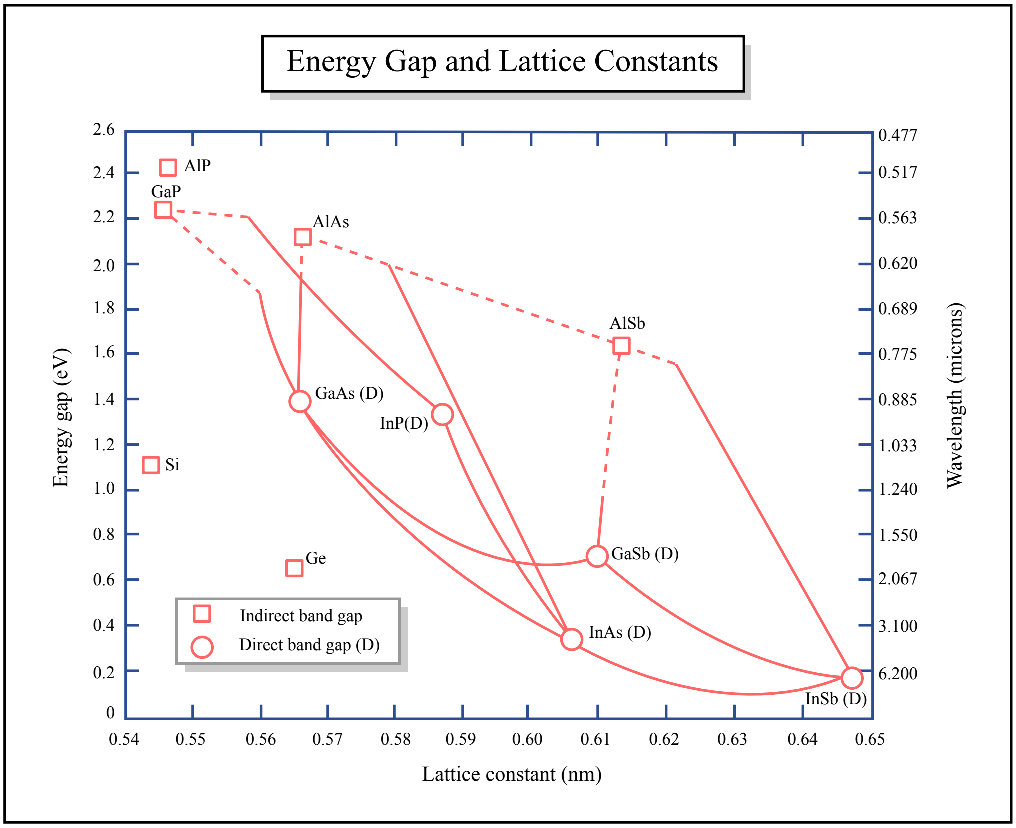
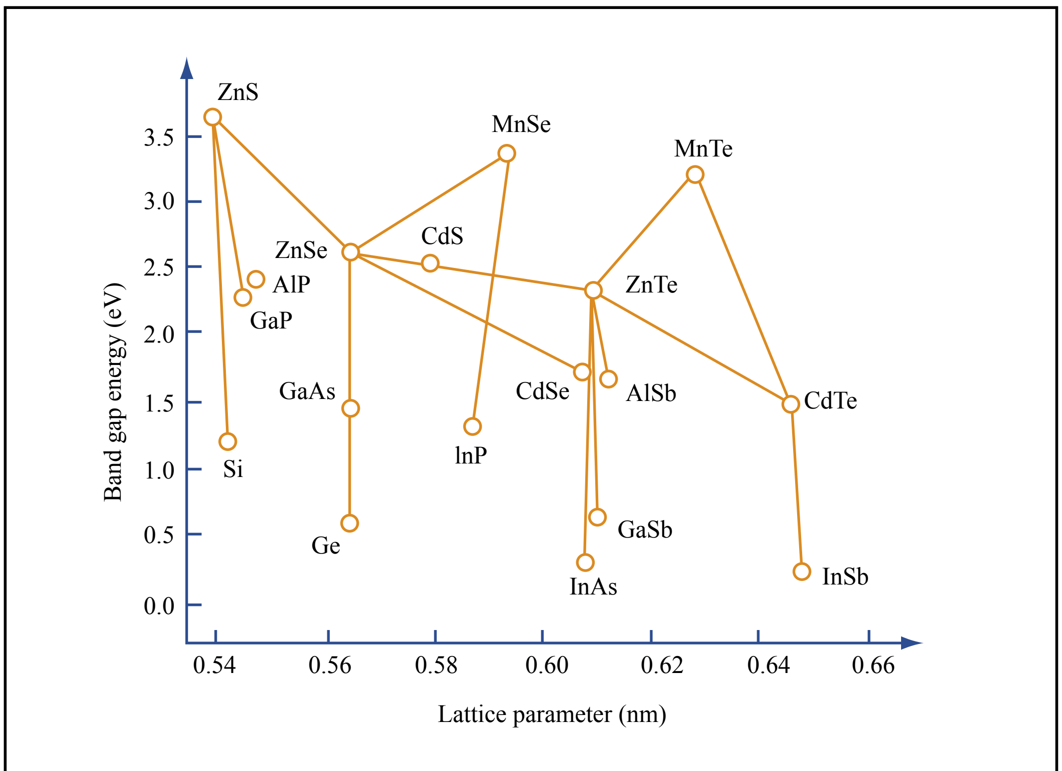


Figure by MIT OCW.



Band gap energies of II - VI compound and alloy semiconductors.

Figure by MIT OCW.

Properties	Si	GaAs	SiO_2	Ge
Atoms/cm^3, molecules/cm^3 x 10^{22}	5.0	4.42	2.27[a]	
Structure	diamond	zincblende	amorphous	
Lattice constant (nm)	0.543	0.565		
Density (g/cm^3)	2.33	5.32	2.27[a]	
Relative dielectric constant, ε_r	11.9	13.1	3.9	
Permittivity, $\varepsilon = \varepsilon_r\varepsilon_o$ (farad/cm) x 10^{-12}	1.05	1.16	0.34	
Expansion coefficient (dL/LdT) x (10^{-6} K)	2.6	6.86	0.5	
Specific Heat (joule/g K)	0.7	0.35	1.0	
Thermal conductivity (watt/cm K)	1.48	0.46	0.014	
Thermal diffusivity (cm^2/sec)	0.9	0.44	0.006	
Energy Gap (eV)	1.12	1.424	~9	0.67
Drift mobility (cm^2/volt-sec)				
Electrons	1500	8500		
Holes	450	400		
Effective density of states				
(cm^{-3}) x 10^{19}				
Conduction band	2.8	0.047		
Valence band	1.04	0.7		
Intrinsic carrier concentration (cm^{-3})	1.45 x 10^{10}	1.79 x 10^6		

Properties of Si, GaAs, SiO_2, and Ge at 300 K

Figure by MIT OCW.

Useful equations

$g_c(E)\,dE = m_n^*\sqrt{\{2m_n^*(E - E_c)\}} / (\pi^2\underline{h}^3)$ ($\underline{h}$ = h-bar)

$g_v(E)\,dE = m_p^*\sqrt{\{2m_p^*(E_v - E)\}} / (\pi^2\underline{h}^3)$

$f(E) = 1/\ \{1 + \exp(E - E_f)/kT\}$

$n = n_i \exp(E_f - E_i)/kT$, $p = n_i \exp(E_i - E_f)/kT$

$n_i = N_c \exp(E_i - E_c)/kT$ where $N_c = 2\{2\pi m_n^* kT/h^2\}^{3/2}$

$np = n_i^2$ at equilibrium

$n_i^2 = N_c N_v \exp(E_v - E_c)/kT = N_c N_v \exp(-E_g)/kT$

$E_i = (E_v + E_c)/2 + 3/4\ kT \ln(m_p^*/\ m_n^*)$

$E_f - E_i = kT \ln(n/\ n_i) = -kT \ln(p/\ n_i)$

$\sim kT \ln(N_D / n_i)$ ntype or $-kT \ln(N_A / n_i)$ ptype

Drift: thermal velocity $1/2\ mv^2_{thermal} = 3/2\ kT$

drift velocity $v_d = \mu\mathbf{E}$ $\mathbf{E}$ = field

Current density (electrons) $J = n\,e\,v_d$

Current density (electrons & holes) $J = e(n\,\mu_n + p\,\mu_h)\mathbf{E}$

Conductivity $\sigma = J/\mathbf{E} = e(n\,\mu_n + p\,\mu_h)$

Diffusion $J = eD_n \nabla n + eD_p \nabla p$

Einstein relation: $D_n/\mu_n = kT/e$

R and G $R = G = rnp = r\,n_i^2$ at equilibrium

$dn/dt = dn/dt_{drift} + dn/dt_{diffn} + dn/dt_{thermal\ RG} + dn/dt_{other\ RG}$

Fick's law $dn/dt_{diffn} = 1/e\ \nabla J_{diffn} = D_n d^2n/dx^2$

so $dn/dt = (1/e)\,\nabla\{J_{drift} + J_{diffn}\} + G - R$

$dn/dt_{thermal} = -\,n_l/\tau_n$ or $dp/dt_{thermal} = -\,p_l/\tau_p$

$\tau_n = 1/rN_A$, or $\tau_p = 1/rN_D$ $L_n = \sqrt{\tau_n D_n}$, or $L_p = \sqrt{\tau_p D_p}$.

If traps dominate $\tau = 1/r_2N_T$ where $r_2 >> r$

pn junction

$\mathbf{E} = 1/\varepsilon_o\varepsilon_r \int \rho(x)\, dx$ where $\rho = e(p - n + N_D - N_A)$

$\mathbf{E} = -dV/dx$

$eV_o = (E_f - E_i)_{n\text{-type}} - (E_f - E_i)_{p\text{-type}}$

$= kT/e \ln (n_n/n_p)$ or $kT/e \ln (N_A N_D/n_i^2)$

$\mathbf{E} = N_A e\, d_p/\varepsilon_o\varepsilon_r = N_D e\, d_p/\varepsilon_o\varepsilon_r$ at $x = 0$

$V_o = (e/2\varepsilon_o\varepsilon_r)(N_D d_n^2 + N_A d_p^2)$

$d_n = \sqrt{\{(2\varepsilon_o\varepsilon_r V_o/e)(N_A/(N_D(N_D + N_A))\}}$

$d = d_p + d_n = \sqrt{\{(2\varepsilon_o\varepsilon_r(V_o + V_A)/e)(N_D + N_A)/N_A N_D\}}$

$J = J_o\{\exp eV_A/kT - 1\}$ where $J_o = en_i^2\{D_p/N_D L_p + D_n/N_A L_n\}$

Transistor BJT gain $\beta = I_C/I_B \sim I_E/I_B = N_{A,E}/N_{D,B}$

$I_E = (eD_p/w)(n_i^2/N_{D,B}) \exp(eV_{EB}/kT)$

JFET $V_{SD,\,sat} = (eN_D t^2/8\varepsilon_o\varepsilon_r) - (V_o + V_G)$

Photodiode and photovoltaic

$I = I_o + I_G$ $V = I(R_{PV} + R_L)$

$I = I_o\{\exp eV/kT - 1\} + I_G$ Power = IV

Wavelength $\lambda(\mu m) = 1.24/E_g\,(eV)$

Band structure

Effective mass: $m^* = \hbar^2(\partial^2 E/\partial k^2)^{-1}$

Momentum of an electron typically $\pi/a \sim 10^{10}\ m^{-1}$

Momentum of a photon $= 2\pi/\lambda \sim 10^7\ m^{-1}$

Uncertainly principle $\Delta x \Delta p \geq \hbar$

Lasers

probability of absorption = B_{13}, stimulated emission = B_{31}, spontaneous emission = A_{31}

$N_3 = N_1 \exp(-h\nu_{31}/kT)$

Planck $\rho(\nu)d\nu = \{8\pi h\nu^3/c^3\}/\{\exp(h\nu/kT) - 1\}\, d\nu$

$B_{13} = B_{31}$

and $A_{31}/B_{31} = 8\pi h\nu^3/c^3$ (Einstein relations)

Cavity modes $\nu = cN/2d$, N an integer.

Fibers

Attenuation (dB) $= \{10/L\} \log(P_{in}/P_{out})$ L = fiber length

Snell's law: $n \sin\phi = n' \sin\phi'$

Dispersion coefft. $D_\lambda = -\{\lambda_o/c\}(\partial^2 n/\partial\lambda^2)_{\lambda=\lambda_o}$ ps/km.nm

$\sigma_t = \sigma_\lambda L D_\lambda$

PHYSICAL CONSTANTS, CONVERSIONS, AND USEFUL COMBINATIONS

Physical Constants

Avogadro constant	$N_A = 6.022 \times 10^{23}$ particles/mole
Boltzmann constant	$k = 8.617 \times 10^{-5}$ eV/K $= 1.38 \times 10^{-23}$ J/K
Elementary charge	$e = 1.602 \times 10^{-19}$ coulomb
Planck constant	$h = 4.136 \times 10^{-15}$ eV ·s
	$= 6.626 \times 10^{-34}$ joule ·s
Speed of light	$c = 2.998 \times 10^{10}$ cm/s
Permittivity (free space)	$\varepsilon_0 = 8.85 \times 10^{-14}$ farad/cm
Electron mass	$m = 9.1095 \times 10^{-31}$ kg
Coulomb constant	$k_c = 8.988 \times 10^9$ newton-m^2/(coulomb)^2
Atomic mass unit	$u = 1.6606 \times 10^{-27}$ kg

Useful Combinations

Thermal energy (300 K)	$kT = 0.0258$ eV $\simeq 1$ eV/40
Photon energy	$E = 1.24$ eV at $\lambda = \mu$m
Coulomb constant	$k_c e^2$ 1.44 eV · nm
Permittivity (Si)	$\varepsilon = \varepsilon_r \varepsilon_0 = 1.05 \times 10^{-12}$ farad/cm
Permittivity (free space)	$\varepsilon_0 = 55.3$e/V · µm

Prefixes

k = kilo = 10^3; M = mega = 10^6; G = giga = 10^9; T = tera = 10^{12}
m = milli = 10^{-3}; µ = micro = 10^{-6}; n = nano = 10^{-9}; p = pica = 10^{-12}

Symbols for Units

Ampere (A), Coulomb (C), Farad (F), Gram (g), Joule (J), Kelvin (K)

Meter (m), Newton (N), Ohm (Ω), Second (s), Siemen (S), Tesla (T)

Volt (V), Watt (W), Weber (Wb)

Conversions

1 nm = 10^{-9} m = 10 Å = 10^{-7} cm; 1 eV = 1.602×10^{-9} Joule = 1.602×10^{-12} erg;
1 eV/particle = 23.06 kcal/mol; 1 newton = 0.102 kg_{force};
10^6 newton/m^2 = 146 psi = 10^7 dyn/cm^2 ; 1 µm = 10^{-4} cm 0.001 inch = 1 mil = 25.4 µm;
1 bar = 10^6 dyn/cm^2 = 10^5 N/m^2; 1 weber/m^2 = 10^4 gauss = 1 tesla;
1 pascal = 1 N/m^2 = 7.5×10^{-3} torr; 1 erg = 10^{-7} joule = 1 dyn-cm

Figure by MIT OCW.