3.15 Electrical, Optical, and Magnetic Materials and Devices
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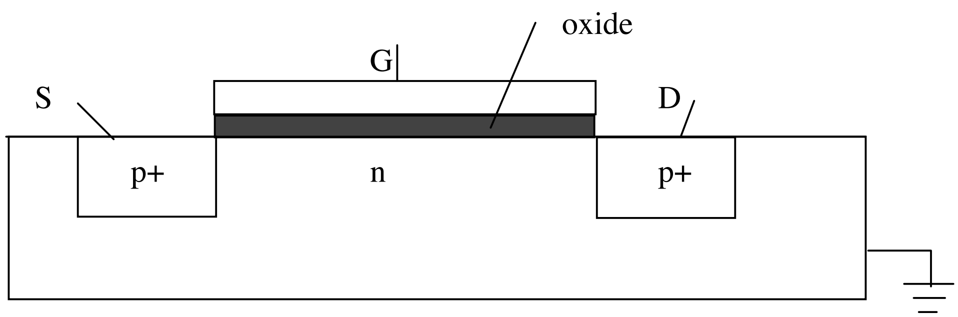
Fall Term, 2005

Exam 2 (5 pages)
Closed book exam. Formulae and data are on the last 3.5 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. MOSFET [20 points]
A MOSFET has the following structure:



a) What happens when you apply a voltage V_G to G (when S and D are grounded)? Consider both positive and negative voltages. Illustrate with a sketch of the MOS band diagram. (10)

b) What happens when you apply a negative voltage V_D to D, for different values of V_G (zero, positive and negative)? (assume S is grounded.) Draw plots of current I_{SD} vs V_D for different values of V_G. (10)

2. Optics [35 points]
a) Draw a diagram of the attenuation of a silica optical fiber vs. wavelength, and explain the shape of the curve. (7)

b) Describe three sources of dispersion in a fiber (one sentence each). (6)

c) We need to design a system to deliver high power laser light of energy 2 eV via a fiber for surgery inside the body. Would you be concerned with dispersion and loss in this application? (4)

d) Select materials for the core, cladding and substrate of the 2 eV laser, explaining your choices. If there is more than one option, which would be preferable? (8)

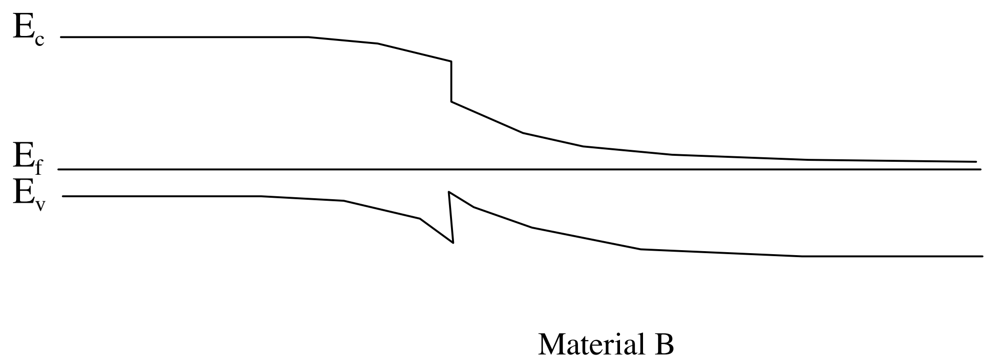
e) It would be nice to have a laser based on Si or Si_xGe_{1-x} ($0 \leq x \leq 1$) because this would be compatible with other silicon devices. What colors of light could you expect from a laser made from SiGe? What is the difficulty with making such a laser? How could this be overcome, and what quality output would the laser produce? (Be concise in this question – no more than 5-6 sentences.) (10)

3. Heterostructures [25 points]

a) Explain concisely the conditions under which a system can act as laser. (No more than 4-5 sentences). Illustrate by describing a ruby or a Nd-YAG laser. (12)

b) Why is a heterostructure better than a homostructure for making a semiconductor laser? (7)

c) A band diagram of a heterostructure is given below. What can you deduce from this diagram about the doping levels of materials A and B? What has happened to materials A and B near the interface? (6)



Data and Formulae

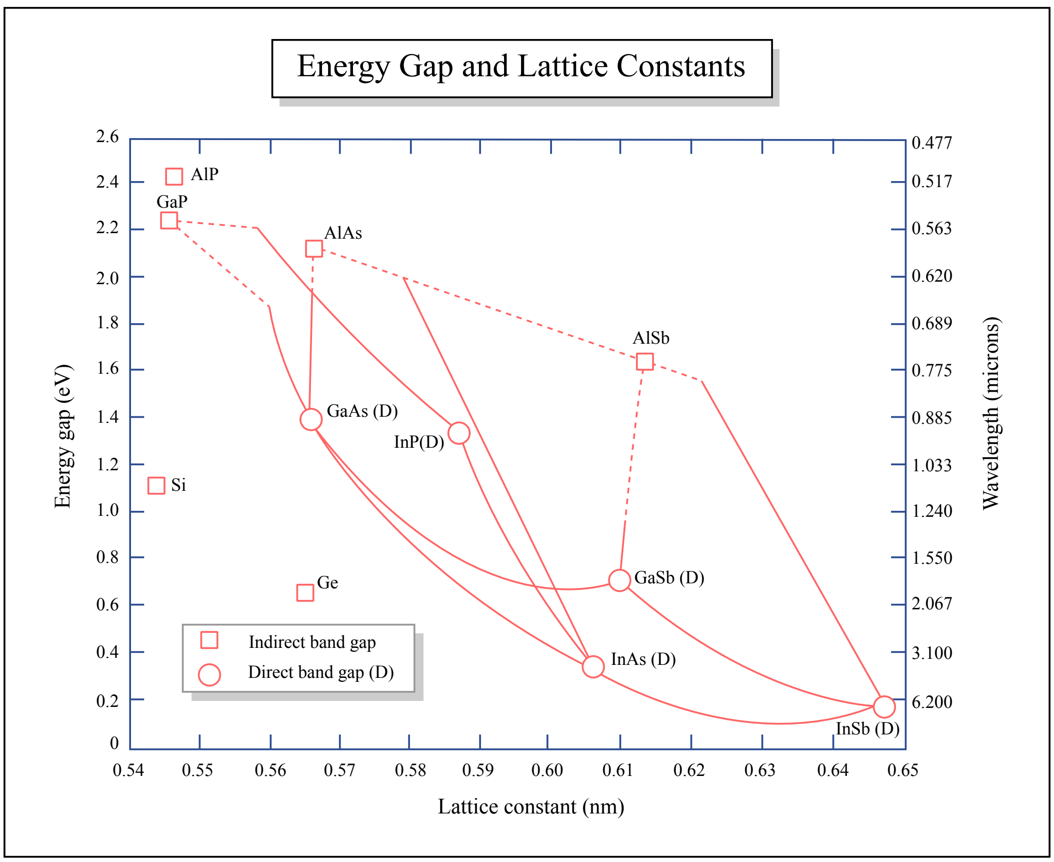


Figure by MIT OCW.

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, SiO2, and Ge at 300 K

Figure by MIT OCW.

<u>Useful equations</u>

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

<u>Drift:</u> 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 $\sigma = J/\mathbf{E} = e\,(n \mu_n + p \mu_h)$

<u>Diffusion</u> $J = eD_n \nabla n + eD_p \nabla p$

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

<u>R and G</u> $R = G = rnp = r\, n_i^2$ 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 $\tau_p = 1/rN_D$ $_n = \sqrt{\tau_n D_n}$, or $_p = \sqrt{\tau_p D_p}$.

If traps dominate $\tau = 1/r_2 N_T$ 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 $J_o = en_i^2 \{D_p/N_D□_p + D_n/N_A□_n\}$

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.