3.15 Electrical, Optical, and Magnetic Materials and Devices
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Exam 1 (4 pages)
Closed book exam. Formulae and data are on the last 2.5 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. [20 points]

a) Draw sketches showing $g_c(E)$, $g_v(E)$, f(E) and the carrier distributions for a semiconductor that is (i) intrinsic, (ii) n-type. (make the sketches with the E axis vertical.) [6]

b) Germanium has the same crystal structure as silicon but its band gap is 0.67 eV.If the total density of states in the conduction band (N_c) and in the valence band (N_v) are the same as they are for silicon, what value of n_i would you expect for Ge at 300K? [6]

c) The Ge is now doped with B and with P. Both dopants have the same concentration. Assume the B and P energy levels are each 40 meV from the band edge. If $m_n^*/m_p^* = 0.01$, draw the band diagram of the doped Ge as accurately as you can, showing E_g, E_f and E_i. [6]

d) What electrical conductivity do you expect for the material in (c) compared to undoped Ge, and why? [2]

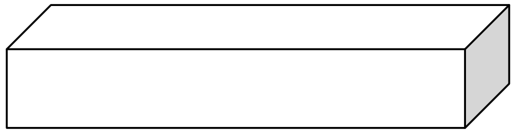
2. [30 points]

a) For a pn junction, draw the electron and hole concentrations vs distance outside the depletion region in the case of no bias, forward bias, and reverse bias, explaining *briefly* the shapes of the graphs. (2-3 sentences) [10]

b) Estimate the voltage you would need to apply to cause avalanche breakdown in a Si pn junction with N_D in the n-side = N_A in the p-side = 10^{15} cm^{-3}. Assume that avalanche breakdown occurs at a field of 10^5 V cm^{-1}, and state any other assumptions you make. [20]

3. [30 points]
a) What factors affect the mobility of a carrier? (2-3 sentences) [6]

b) A piece of p-type Si with $N_A = 10^{18}$ cm^{-3} and a length of 1 cm is heated at one end. This affects the value of n_i as follows:



Hot $n_i = 10^{12}$ cm^{-3} Cold $n_i = 10^{10}$ cm^{-3}

Consider only the electrons in the Si, neglecting the motion of the holes. Where do drift and diffusion of the electrons occur? Estimate the electric field at the cold end of the Si. [16]

c) A BJT can be used to detect light by allowing the light to fall on the base region. How could you bias the two junctions in the BJT to get a good response to light? For your biasing scheme, draw the band structure and explain where the current(s) flow. [8]

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.

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 $\cdot$s
	$= 6.626 \times 10^{-34}$ joule $\cdot$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 $\cdot$ nm
Permittivity (Si)	$\varepsilon = \varepsilon_r \varepsilon_0 = 1.05 \times 10^{-12}$ farad/cm
Permittivity (free space)	$\varepsilon_0 = 55.3e/V \cdot \mu$m

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

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 $\tau_p = 1/rN_D$ $\square_n = \sqrt{\tau_n D_n}$, or $\square_p = \sqrt{\tau_p D_p}$.

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 $J_o = e n_i^2 \{D_p/N_D \square_p + D_n/N_A \square_n\}$

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