3.15 Electrical, Optical, and Magnetic Materials and Devices
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Exam 1 (3 pages)
Closed book exam. Formulae and data are on the last 2 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. A thick slab of Si (p-type, $N_A = 10^{18}$ cm^{-3}), is illuminated on one side with light. The light creates an extra 10^{10} electron-hole pairs cm^{-2} s^{-1} in the top 1 μm of the Si. The lifetime of the carriers is 10^{-5} s, and their diffusivity can be taken as 40 cm^2 s^{-1} (neglect the difference between electrons and holes).

a) Draw a plot of *both* p and n vs. distance x into the Si, as accurately as you can. You should calculate the concentrations at the surface. [10]

b) For the electrons, derive a steady-state expression that shows how their concentration varies with distance into the Si, explaining your reasoning. [10]

c) Suppose the Si is only 100 μm thick. Is there a significant change in conductivity due to the light? Justify your answer with a calculation or estimate. [10]

2. a) For a BJT in *forward active mode*, explain concisely what factor(s) determine the current gain β, and why. (3-4 sentences) [10]

b) The BJT is now biased so that it is in the *saturated mode*. Draw a band structure of the biased BJT (assume it is pnp) and explain what is going on at each junction and where the current flows in the device. (3-4 sentences) [10]

3. InSb is a semiconductor with a band gap of 0.2 eV and mobilities of 80,000 cm^2 V^{-1} s^{-1} for electrons and 750 cm^2 V^{-1} s^{-1} for holes. The effective masses are $0.001m_o$ for electrons and $0.1m_o$ for holes. $N_c = 10^{18}$ cm^{-3} and $N_v = 10^{19}$ cm^{-3}.

a) What intrinsic carrier concentration would you expect in *undoped* InSb? For *doped* InSb (with $N_D = 10^{18}$ cm^{-3}) what conductivity would you expect? [10]

b) Draw a plot of density of states vs energy (with the energy axis vertical), indicating quantitatively where the Fermi energy is. Show schematically the occupation of the intrinsic electrons and holes on this plot. [10]

c) You now make a pn junction between n-type InSb and p-type Si. Draw a sketch of what the band structure might look like at equilibrium and show where there are diffusion and drift currents. [10]

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 x 10^{23} particles/mole
Boltzmann constant	k = 8.617 x 10^{-5} eV/K = 1.38 x 10^{-23} J/K
Elementary charge	e = 1.602 x 10^{-19} coulomb
Planck constant	h = 4.136 x 10^{-15} eV ·s = 6.626 x 10^{-34} joule ·s
Speed of light	c = 2.998 x 10^{10} cm/s
Permittivity (free space)	ε_0 = 8.85 x 10^{-14} farad/cm
Electron mass	m = 9.1095 x 10^{-31} kg
Coulomb constant	k_c = 8.988 x 10^9 newton-m^2/(coulomb)^2
Atomic mass unit	u = 1.6606 x 10^{-27} kg

Useful Combinations

Thermal energy (300 K)	kT = 0.0258 eV $\simeq$ 1 eV/40
Photon energy	E = 1.24 eV at λ = µm
Coulomb constant	$k_c e^2$ 1.44 eV · nm
Permittivity (Si)	$\varepsilon = \varepsilon_r \varepsilon_0$ = 1.05 x 10^{-12} farad/cm
Permittivity (free space)	ε_0 = 55.3e/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 x 10^{-9} Joule = 1.602 x 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 x 10^{-3} torr; 1 erg = 10^{-7} joule = 1 dyn-cm

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 $N_c = 2\{2\pi m_n^* kT/h^2\}^{3/2}$

or $n_i = N_v \exp(E_v - E_i)/kT$ where $N_v = 2\{2\pi m_p^* kT/h^2\}^{3/2}$

$np = n_i^2$ 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 $\tau = 1/r_2 N_T$ 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 $J_o = en_i^2\{D_p/N_D L_p + D_n/N_A L_n\}$

Transistor BJT gain $\beta = I_C/I_B \sim I_E/I_B$

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