GATE 2027 EC, Section 3

Electronic devices

Semiconductor physics, carrier transport, PN junction, BJT, MOS capacitor and MOSFET, scaling, LED, photodiode and solar cell.

43 formulas in 7 topics. Equations are numbered section.topic.formula, for example (3.1.1).

3.1 Constants (300 K)

Charge, Boltzmann (3.1.1)

$q = 1.6 \times 10^{-19}$ C; $k = 1.38 \times 10^{-23}$ J/K $= 8.62 \times 10^{-5}$ eV/K

Thermal voltage (3.1.2)

$V_T = kT/q \approx 25.9$ mV (≈ 26 mV)

Silicon (3.1.3)

$E_g \approx 1.12$ eV (indirect); $n_i \approx 1 \times 10^{10}$ cm^{-3} (1.5×10^{10} in older texts)

Others (3.1.4)

Ge $E_g \approx 0.66$ eV (indirect); GaAs $E_g \approx 1.42$ eV (direct)

Wavelength–bandgap (3.1.5)

$\lambda\ (\mu m) \approx 1.24 / E_g\ (eV)$

3.2 Carriers

Mass-action law (3.2.1)

$n \cdot p = {n_i}^2$

Carrier concentrations (3.2.2)

$n = N_c\, e^{-(E_c - E_F)/kT}$; $p = N_v\, e^{-(E_F - E_v)/kT}$

Intrinsic concentration (3.2.3)

$n_i = \sqrt{(N_c N_v)}\, e^{-E_g/2kT}$

n-type ($N_D \gg n_i$) (3.2.4)

$n \approx N_D$; $p = {n_i}^2/N_D$; $E_F - E_i = kT \ln(N_D/n_i)$

p-type ($N_A \gg n_i$) (3.2.5)

$p \approx N_A$; $n = {n_i}^2/N_A$; $E_i - E_F = kT \ln(N_A/n_i)$

3.3 Carrier transport

Conductivity (3.3.1)

$\sigma = q(n\mu_n + p\mu_p)$; $\rho = 1/\sigma$

Drift current (3.3.2)

$J = q(n\mu_n + p\mu_p)E$

Diffusion current (3.3.3)

$J_n = qD_n\, dn/dx$; $J_p = -qD_p\, dp/dx$

Einstein relation (3.3.4)

$D/\mu = kT/q = V_T$

Diffusion length (3.3.5)

$L = \sqrt{(D\tau)}$

Continuity (holes) (3.3.6)

$\partial p/\partial t = -(1/q)\partial J_p/\partial x + G_p - (p - p_0)/\tau_p$

Poisson (3.3.7)

$d^2V/dx^2 = -\rho/\varepsilon$; $dE/dx = \rho/\varepsilon$

Hall effect (3.3.8)

$V_H = BI/(qnt)$; $R_H = 1/(qn)$

3.4 PN junction and diodes

Built-in potential (3.4.1)

$V_0 = V_T \ln(N_A \cdot N_D/{n_i}^2)$

Depletion width (3.4.2)

$W = \sqrt{[(2\varepsilon(V_0 - V)/q)(1/N_A + 1/N_D)]}$ ($V > 0$ forward)

Charge balance (3.4.3)

$x_n N_D = x_p N_A$ (lightly doped side holds most of W)

Diode equation (3.4.4)

$I = I_s(e^{V/\eta V_T} - 1)$

Small-signal resistance (3.4.5)

$r_d = \eta V_T / I$

Junction capacitance (3.4.6)

$C_j = \varepsilon A / W \propto (V_0 - V)^{-1/2}$ for an abrupt junction

Diffusion capacitance (3.4.7)

$C_d = \tau I / (\eta V_T)$

Temperature (3.4.8)

I_s roughly doubles every 10 °C; V_D falls ≈ 2 mV/°C

Zener (3.4.9)

Zener breakdown below ~5 V (heavy doping, negative tempco); avalanche above ~7 V (positive tempco)

3.5 BJT

Currents (3.5.1)

$I_E = I_C + I_B$; $I_C = \beta I_B = \alpha I_E$

α and β (3.5.2)

$\alpha = \beta / (\beta + 1)$; $\beta = \alpha / (1 - \alpha)$

Active region (3.5.3)

$I_C = I_s \, e^{V_{BE}/V_T}$

Small-signal (3.5.4)

$g_m = I_C / V_T$; $r_\pi = \beta / g_m$; $r_o = V_A / I_C$

3.6 MOS capacitor and MOSFET

Oxide capacitance (3.6.1)

$C_{ox} = \varepsilon_{ox} / t_{ox}$ (per unit area)

MOS-C regions (3.6.2)

Accumulation → $C = C_{ox}$; depletion → C_{ox} in series with C_{dep}; strong inversion (low f) → C_{ox}

Triode ($V_{DS} < V_{GS} - V_t$) (3.6.3)

$I_D = \mu_n C_{ox} (W/L) [(V_{GS} - V_t) V_{DS} - V_{DS}^2 / 2]$

Saturation (3.6.4)

$I_D = \tfrac{1}{2} \mu_n C_{ox} (W/L) (V_{GS} - V_t)^2 (1 + \lambda V_{DS})$

Transconductance (3.6.5)

$g_m = \mu_n C_{ox} (W/L) (V_{GS} - V_t) = 2 I_D / (V_{GS} - V_t) = \sqrt{(2 \mu_n C_{ox} (W/L) I_D)}$

Output resistance (3.6.6)

$r_o = 1 / (\lambda I_D)$

Body effect (3.6.7)

$V_t = V_{t0} + \gamma (\sqrt{(2\varphi_F + V_{SB})} - \sqrt{(2\varphi_F)})$

Constant-field scaling by κ (3.6.8)

L, W, t_{ox}, V ÷ κ; doping × κ; delay ÷ κ; power per device ÷ κ^2; power density unchanged

3.7 Optoelectronic devices

Photon energy (3.7.1)

$E = hf = hc / \lambda$

Photodiode responsivity (3.7.2)

$R = \eta q / (hf) \approx \eta \lambda(\mu m) / 1.24$ A/W

Solar cell (3.7.3)

$V_{oc} = V_T \ln(1 + I_L / I_s)$; $FF = P_{max} / (V_{oc} I_{sc})$; efficiency $= P_{max} / P_{in}$

LED (3.7.4)

Emission wavelength set by bandgap; direct-gap materials emit efficiently

My notes