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Electronic Devices Formula Sheet

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Energy bands and carrier concentration

FERMI–DIRAC DISTRIBUTION

$$f(E) = \frac{1}{1 + \exp\left(\dfrac{E - E_F}{kT}\right)}$$

Probability that an allowed state at energy E is occupied by an electron, in thermal equilibrium. $k = 8.62 \times 10^{-5}\,\mathrm{eV/K}$. For any $T > 0$, $f(E_F) = \frac{1}{2}$. At $T = 0\,\mathrm{K}$, $f = 1$ for $E < E_F$ and $f = 0$ for $E > E_F$.

PROBABILITY THAT A STATE IS EMPTY (HOLE OCCUPANCY)

$$1 - f(E) = \frac{1}{1 + \exp\left(\dfrac{E_F - E}{kT}\right)}$$

Used for holes in the valence band; follows directly from $f(E)$.

EQUILIBRIUM ELECTRON AND HOLE CONCENTRATIONS

$$n_0 = N_c \exp\left(-\frac{E_c - E_F}{kT}\right), \qquad p_0 = N_v \exp\left(-\frac{E_F - E_v}{kT}\right)$$

Valid in thermal equilibrium for a non-degenerate semiconductor (E_F at least about $3kT$ from E_c and from E_v), whatever the doping. N_c and N_v are the effective densities of states of the conduction and valence bands.

EFFECTIVE DENSITIES OF STATES

$$N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}, \qquad N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$$

In SI units these come out in $\mathrm{m^{-3}}$; divide by 10^6 for $\mathrm{cm^{-3}}$. Both scale as $(m^*)^{3/2}T^{3/2}$, so they depend on the carrier effective masses and rise with temperature. They are material properties, not constants: in a numerical problem, use the values given.

INTRINSIC CARRIER CONCENTRATION

$$n_i = \sqrt{N_c N_v}\,\exp\left(-\frac{E_g}{2kT}\right)$$

Holds in thermal equilibrium, non-degenerate; $E_g = E_c - E_v$. For silicon at $T = 300\,\mathrm{K}$ the commonly used value is $n_i \approx 1.5 \times 10^{10}\,\mathrm{cm^{-3}}$ (some texts use $1.0 \times 10^{10}\,\mathrm{cm^{-3}}$). n_i depends on the material and the temperature, so always use the value the problem states.

TEMPERATURE DEPENDENCE OF N_I

$$n_i^2 = N_c N_v \exp\left(-\frac{E_g}{kT}\right) \propto T^3 \exp\left(-\frac{E_g}{kT}\right)$$

This follows from $N_c N_v \propto T^3$, and the exponential factor dominates. Taking E_g as constant, two temperatures are related by $\dfrac{n_i(T_2)}{n_i(T_1)} = \left(\dfrac{T_2}{T_1}\right)^{3/2} \exp\left[\dfrac{E_g}{2k}\left(\dfrac{1}{T_1} - \dfrac{1}{T_2}\right)\right]$.

INTRINSIC FERMI LEVEL

$$E_i = \frac{E_c + E_v}{2} + \frac{kT}{2}\ln\left(\frac{N_v}{N_c}\right) = \frac{E_c + E_v}{2} + \frac{3}{4}kT\ln\left(\frac{m_p^*}{m_n^*}\right)$$

Obtained by setting $n_0 = p_0$ in the Boltzmann expressions. If $m_p^* > m_n^*$, E_i lies slightly above mid-gap. The shift is of order kT, small compared with E_g.

CARRIER CONCENTRATIONS REFERRED TO E_I

$$n_0 = n_i \exp\left(\frac{E_F - E_i}{kT}\right), \qquad p_0 = n_i \exp\left(\frac{E_i - E_F}{kT}\right)$$

Equivalent to the N_c, N_v forms and valid under the same conditions (equilibrium, non-degenerate, any doping). Multiplying the two gives $n_0 p_0 = n_i^2$ directly.

FERMI LEVEL POSITION, N-TYPE

$$E_F - E_i = kT \ln\left(\frac{n_0}{n_i}\right), \qquad E_c - E_F = kT \ln\left(\frac{N_c}{n_0}\right)$$

From the Boltzmann expressions; non-degenerate, equilibrium. E_F lies above E_i when $n_0 > n_i$.

FERMI LEVEL POSITION, P-TYPE

$$E_i - E_F = kT \ln\left(\frac{p_0}{n_i}\right), \qquad E_F - E_v = kT \ln\left(\frac{N_v}{p_0}\right)$$

From the Boltzmann expressions; non-degenerate, equilibrium. E_F lies below E_i when $p_0 > n_i$.

MASS-ACTION LAW

$$n_0\, p_0 = n_i^2$$

Holds in thermal equilibrium in a non-degenerate semiconductor, doped or undoped, with n_i evaluated at the same temperature. It does **not** hold under illumination or carrier injection (non-equilibrium).

CHARGE NEUTRALITY (GENERAL)

$$n_0 + N_a^- = p_0 + N_d^+$$

Total negative charge equals total positive charge in the bulk, where N_a^- and N_d^+ are the **ionised** acceptor and donor concentrations. With full ionisation, $N_a^- = N_a$ and $N_d^+ = N_d$.

COMPENSATED DOPING (FULL IONISATION)

$$n_0 - p_0 = N_d - N_a$$

Combine with $n_0 p_0 = n_i^2$ to solve for n_0 and p_0. If $|N_d - N_a| \gg n_i$, the material is n-type when $N_d > N_a$ (then $n_0 \approx N_d - N_a$) and p-type when $N_a > N_d$ (then $p_0 \approx N_a - N_d$); the minority carrier follows from mass action.

EXACT EQUILIBRIUM SOLUTION ($N_D > N_A$)

$$n_0 = \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}, \qquad p_0 = \frac{n_i^2}{n_0}$$

This is the positive root of $n_0^2 - (N_d - N_a) n_0 - n_i^2 = 0$ (full ionisation, non-degenerate). For $N_a > N_d$ swap the roles: $p_0 = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2}$. Needed whenever $|N_d - N_a|$ is not much larger than n_i. With $N_d = N_a$ it gives $n_0 = p_0 = n_i$.

THERMAL VOLTAGE

$$V_T = \frac{kT}{q}$$

$V_T \approx 25.9\,\text{mV}$ at $T = 300\,\text{K}$, with $k = 1.38 \times 10^{-23}\,\text{J/K}$ and $q = 1.6 \times 10^{-19}\,\text{C}$. Equivalently $kT \approx 0.0259\,\text{eV}$ at 300 K, so an energy difference in eV divided by kT in eV gives the dimensionless exponent in the Boltzmann expressions directly.

EFFECTIVE MASS FROM THE E–K DIAGRAM

$$m^* = \frac{\hbar^2}{(d^2E/dk^2)}$$

Evaluated at the band edge, with $\hbar = h/2\pi$. A sharply curved band gives a small effective mass. For a parabolic conduction band, $E = E_c + \dfrac{\hbar^2 k^2}{2m_n^*}$.

BAND-GAP WAVELENGTH

$$\lambda = \frac{hc}{E_g} \quad \Rightarrow \quad \lambda\,(\mu\text{m}) \approx \frac{1.24}{E_g\,(\text{eV})}$$

The wavelength of a photon of energy E_g. It gives the approximate emission wavelength of band-to-band recombination and the longest wavelength (cut-off) the material absorbs band-to-band. Uses $hc \approx 1.24\,\text{eV}\,\mu\text{m}$.

Carrier transport: drift, diffusion, generation and recombination

DRIFT VELOCITY AND MOBILITY

$$v_{dn} = -\mu_n E \qquad v_{dp} = \mu_p E \qquad \mu = \frac{q\tau_m}{m^*}$$

Electrons drift opposite to E (hence the minus sign) and holes drift along E. μ_n, μ_p are the electron and hole mobilities in $\text{cm}^2/\text{V-s}$. τ_m is the mean time between scattering events and m^* is the conductivity effective mass. The linear relation $v_d = \mu E$ holds only at low fields (see velocity saturation below).

DRIFT CURRENT DENSITY

$$J_{n,\text{drift}} = qn\mu_n E \qquad J_{p,\text{drift}} = qp\mu_p E \qquad J_{\text{drift}} = q(n\mu_n + p\mu_p)E$$

$q = 1.6 \times 10^{-19}$ C. With n, p in cm^{-3} and E in V/cm, J is in A/cm^2. Electron and hole drift currents both point along E (conventional current), so they add.

CONDUCTIVITY AND RESISTIVITY

$$\sigma = q(n\mu_n + p\mu_p) \qquad \rho = \frac{1}{\sigma} \qquad R = \frac{\rho L}{A}$$

For a fully ionized, uncompensated extrinsic sample with doping much larger than n_i, one term dominates: $\sigma \approx qN_D\mu_n$ (n-type) or $\sigma \approx qN_A\mu_p$ (p-type). In a compensated sample, use the net doping, e.g. $n \approx N_D - N_A$ when $N_D - N_A \gg n_i$. The mobility is still reduced by all $N_D + N_A$ ionized impurities. For an intrinsic sample, $\sigma_i = qn_i(\mu_n + \mu_p)$. L is the length along the current and A the cross-section.

MINIMUM CONDUCTIVITY

$$\sigma = q\left(n\mu_n + \frac{n_i^2}{n}\mu_p\right) \;\Rightarrow\; \sigma_{min} = 2qn_i\sqrt{\mu_n\mu_p} \text{ at } n = n_i\sqrt{\frac{\mu_p}{\mu_n}}$$

This uses $np = n_i^2$ (thermal equilibrium, non-degenerate). Since $\mu_n > \mu_p$ in Si, the minimum lies at $n < n_i$, i.e. in slightly p-type material, not at the intrinsic point. $\sigma_{min} < \sigma_i$ because $2\sqrt{\mu_n\mu_p} \le \mu_n + \mu_p$.

DIFFUSION CURRENT DENSITY

$$J_{n,\text{diff}} = qD_n\frac{dn}{dx} \qquad J_{p,\text{diff}} = -qD_p\frac{dp}{dx}$$

D_n, D_p are diffusion coefficients in cm^2/s. Both carriers diffuse from high to low concentration. Electrons are negative, so the electron diffusion current points up the electron gradient (it has the sign of dn/dx). Holes are positive, so the hole diffusion current points down the hole gradient (it has the sign of $-dp/dx$).

TOTAL CURRENT DENSITY (1-D)

$$J_n = qn\mu_n E + qD_n\frac{dn}{dx} \qquad J_p = qp\mu_p E - qD_p\frac{dp}{dx} \qquad J = J_n + J_p$$

The drift-diffusion equations for each carrier type. They are the inputs to the continuity equation.

EINSTEIN RELATION

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{q} = V_T$$

Holds for a non-degenerate semiconductor. It is derived in thermal equilibrium and used at low fields in the drift-diffusion model. $V_T \approx 0.02585$ V at $T = 300$ K, often rounded to 0.0259 V or 0.026 V. State the value you use, because the rounding shifts the third significant figure.

BUILT-IN FIELD FROM NON-UNIFORM DOPING

$$E(x) = -V_T \frac{1}{N_D(x)} \frac{dN_D}{dx} \text{ (n-type)} \qquad E(x) = V_T \frac{1}{N_A(x)} \frac{dN_A}{dx} \text{ (p-type)}$$

Conditions: thermal equilibrium (zero net current), full ionization, and quasi-neutrality ($n \approx N_D(x)$ or $p \approx N_A(x)$). Drift must cancel diffusion, so a doping gradient produces a field. Example: $N_D = N_0 e^{-x/\lambda}$ gives a uniform field $E = V_T/\lambda$ along $+x$.

HALL VOLTAGE AND HALL COEFFICIENT

$$V_H = \frac{R_H I B}{t} \qquad R_H = \frac{1}{qp} \text{ (p-type)}, \quad R_H = -\frac{1}{qn} \text{ (n-type)} \qquad E_H = \frac{V_H}{W} = R_H J B$$

I flows along the sample length and B is perpendicular to I. t is the sample thickness measured along B, W is the width across which V_H is measured, and $J = I/(Wt)$. V_H does not depend on W. For a fixed geometry, V_H has opposite polarity for holes and for electrons, so the sign of V_H (or R_H) identifies the majority carrier. These simple forms assume one dominant carrier type and take the Hall scattering factor as 1. From a measured V_H: $p = IB/(qV_H t)$ or $n = IB/(q|V_H|t)$.

HALL MOBILITY

$$\mu_H = |R_H|\,\sigma = \frac{|R_H|}{\rho}$$

Valid when one carrier type dominates. It combines the measured Hall coefficient and the measured conductivity to give the majority-carrier mobility.

NET RECOMBINATION RATE (LOW-LEVEL INJECTION)

$$R - G_{th} = \frac{\delta p}{\tau_p} \text{ (n-type)} \qquad R - G_{th} = \frac{\delta n}{\tau_n} \text{ (p-type)}$$

Valid for low-level injection, where the excess carrier density is much smaller than the majority-carrier density. $\delta p = p - p_0$ and $\delta n = n - n_0$ are the excess concentrations. In a neutral region with pair generation, $\delta n = \delta p$. τ_p, τ_n are the minority-carrier lifetimes; they depend on the material and its defects and are given as constants in problems.

UNIFORM GENERATION: STEADY STATE, DECAY AND PHOTOCONDUCTIVITY

$$\delta p = G_L \tau_p \text{ (steady state)} \qquad \delta p(t) = \delta p(0)\, e^{-t/\tau_p} \text{ (after } G_L \text{ is switched off)} \qquad \Delta\sigma = q(\mu_n + \mu_p)\,\delta p$$

Conditions: a uniformly illuminated n-type sample, low-level injection, and no concentration gradients (so no diffusion). The continuity equation then reduces to $d(\delta p)/dt = G_L - \delta p/\tau_p$. G_L is the optical generation rate in $\mathrm{cm^{-3}s^{-1}}$. Since $\delta n = \delta p$, both carriers add to the conductivity.

DIFFUSION LENGTH

$$L_p = \sqrt{D_p \tau_p} \qquad L_n = \sqrt{D_n \tau_n}$$

The characteristic distance a minority carrier diffuses before it recombines. In a long sample it is the $1/e$ decay length of the steady-state excess-carrier profile (see the continuity-equation section).

CONTINUITY EQUATIONS (1-D)

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} + G_n - R_n \qquad \frac{\partial p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} + G_p - R_p$$

G and R are the generation and recombination rates. The opposite signs come from the charge of each carrier: $J_n = -q\times$(electron flux) and $J_p = +q\times$(hole flux). Substituting the drift-diffusion expressions for J_n and J_p gives the minority-carrier equation below.

MINORITY-CARRIER (HOLE) EQUATION IN AN N-TYPE SAMPLE

$$D_p\frac{\partial^2(\delta p)}{\partial x^2} - \mu_p E\frac{\partial(\delta p)}{\partial x} - \frac{\delta p}{\tau_p} + G_{ext} = \frac{\partial(\delta p)}{\partial t}$$

Assumes uniform doping, a uniform field E and low-level injection. G_{ext} is any externally driven generation, e.g. optical. With $E = 0$ the drift term drops out. Setting the time derivative to zero gives the steady-state form.

STEADY-STATE SOLUTION, LONG SAMPLE (E = 0)

$$\delta p(x) = \delta p(0)\, e^{-x/L_p}, \qquad L_p = \sqrt{D_p\tau_p}, \qquad J_p(x) = \frac{qD_p\,\delta p(0)}{L_p}\, e^{-x/L_p}$$

Conditions: no generation for $x > 0$, the excess concentration held at $\delta p(0)$ (e.g. by an injecting junction), and $\delta p \to 0$ as $x \to \infty$ (sample length much greater than L_p). The diffusion current decays with the same length L_p as the profile.

STEADY-STATE SOLUTION, SAMPLE OF LENGTH W (E = 0)

$$\delta p(x) = \delta p(0)\,\frac{\sinh\left((W-x)/L_p\right)}{\sinh\left(W/L_p\right)} \;\approx\; \delta p(0)\left(1 - \frac{x}{W}\right) \text{ for } W \ll L_p$$

The same equation with $\delta p(W) = 0$, as at an ohmic contact or a reverse-biased junction at $x = W$. When $W \ll L_p$, almost no carriers recombine in transit. The profile is then linear, and the diffusion current $qD_p\,\delta p(0)/W$ is nearly uniform. This is the short-base picture used for BJTs and short diodes.

POISSON'S EQUATION (1-D)

$$\frac{dE}{dx} = \frac{\rho_{net}}{\epsilon_s} \qquad \frac{d^2V}{dx^2} = -\frac{\rho_{net}}{\epsilon_s} \qquad \rho_{net} = q\left(p - n + N_D^+ - N_A^-\right)$$

$E = -dV/dx$. ρ_{net} here is the space-charge density, not resistivity. $\epsilon_s = \epsilon_r\epsilon_0$ is the semiconductor permittivity, with $\epsilon_r \approx 11.7$–11.9 for Si and $\epsilon_0 = 8.85 \times 10^{-14}$ F/cm. With the depletion approximation ($n, p \approx 0$ inside the depletion region), it gives the field and potential profiles and the depletion width of a junction. For example, on the n-side of a step junction $dE/dx = qN_D/\epsilon_s$, so E varies linearly with x.

QUASI-FERMI LEVELS

$$n = n_i\, e^{(E_{Fn}-E_i)/kT} \qquad p = n_i\, e^{(E_i-E_{Fp})/kT} \qquad np = n_i^2\, e^{(E_{Fn}-E_{Fp})/kT}$$

Valid for a non-degenerate semiconductor. With no excess generation or injection, both reduce to the single equilibrium Fermi level ($E_{Fn} = E_{Fp} = E_F$, $np = n_i^2$). Quoted values of n_i for Si at 300 K range from about 9.65×10^9 to $1.5 \times 10^{10}\ \mathrm{cm}^{-3}$. Use the value the question gives, and state it whenever a numerical answer depends on it.

P-N junctions and Zener diodes

BUILT-IN POTENTIAL

$$V_{bi} = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

Holds at thermal equilibrium with complete ionization and non-degenerate doping (N_A, N_D well below the effective densities of states). N_A and N_D are the net acceptor and donor concentrations on the two sides. V_{bi} is positive: the n-side sits V_{bi} above the p-side. It cannot be read with a voltmeter across the diode, because the contact potentials at the metal contacts cancel it.

BUILT-IN POTENTIAL FROM CARRIER RATIOS

$$V_{bi} = V_T \ln\left(\frac{n_{n0}}{n_{p0}}\right) = V_T \ln\left(\frac{p_{p0}}{p_{n0}}\right)$$

Equilibrium majority and minority concentrations on the two sides, with $n_{n0} \approx N_D$ and $p_{p0} \approx N_A$. This is the same result as above, written with the mass-action law.

DEPLETION WIDTH (STEP/ABRUPT JUNCTION)

$$W = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_{bi} - V_A)}$$

For an abrupt (step) junction under the depletion approximation. It holds in reverse bias and in forward bias only while V_A stays well below V_{bi}; the approximation fails as $V_A \to V_{bi}$. In reverse bias $V_A = -V_R$, so the bracket becomes $V_{bi} + V_R$ and W grows. $\epsilon_s = \epsilon_r \epsilon_0$; for Si, $\epsilon_r \approx 11.7$, giving $\epsilon_s \approx 1.04 \times 10^{-12}\ \mathrm{F/cm}$.

CHARGE BALANCE AND INDIVIDUAL DEPLETION WIDTHS

$$N_A x_p = N_D x_n, \qquad x_n = W\frac{N_A}{N_A + N_D}, \qquad x_p = W\frac{N_D}{N_A + N_D}$$

Charge neutrality: the ionized charge on the two sides is equal and opposite. The more lightly doped side always holds most of W.

PEAK ELECTRIC FIELD (STEP JUNCTION)

$$E_{max} = \frac{qN_D x_n}{\epsilon_s} = \frac{qN_A x_p}{\epsilon_s} = \frac{2\,(V_{bi} - V_A)}{W}$$

The peak is at the metallurgical junction ($x = 0$). The field falls linearly to zero at each depletion edge, so the profile is a triangle whose area equals $V_{bi} - V_A$.

DEPLETION WIDTH (LINEARLY GRADED JUNCTION)

$$W = \left[\frac{12\,\epsilon_s\,(V_{bi} - V_A)}{q\,a}\right]^{1/3}$$

For a doping profile $N_D - N_A = ax$ that changes linearly through the junction, where a is the grading constant in cm^{-4}. Here $W \propto (V_{bi} - V_A)^{1/3}$, compared with the square-root dependence of the step junction.

DEPLETION CAPACITANCE (GENERAL)

$$C_j = \frac{\epsilon_s A}{W}$$

A is the junction cross-sectional area and W is the depletion width at the bias point. This holds for any doping profile as a small-signal capacitance.

DEPLETION CAPACITANCE VS BIAS

$$C_j(V_A) = \frac{C_{j0}}{\left(1 - \dfrac{V_A}{V_{bi}}\right)^m}$$

C_{j0} is the capacitance at zero bias. The grading exponent is $m = 1/2$ for an abrupt junction and $m = 1/3$ for a linearly graded one. In reverse bias $V_A = -V_R$, so the bracket is $1 + V_R/V_{bi}$ and $C_j < C_{j0}$. The formula applies in reverse bias and at small forward bias only; it wrongly diverges as $V_A \to V_{bi}$.

1/C_J^2 VS REVERSE BIAS (ONE-SIDED ABRUPT JUNCTION)

$$\frac{1}{C_j^2} = \frac{2\,(V_{bi} + V_R)}{q\,\epsilon_s N_B A^2}$$

N_B is the doping of the lightly doped side. A plot of $1/C_j^2$ against V_R is a straight line: its slope gives N_B, and its intercept on the voltage axis is at $V_R = -V_{bi}$.

LAW OF THE JUNCTION

$$p_n(x_n) = p_{n0}\, e^{V_A/V_T}, \qquad n_p(-x_p) = n_{p0}\, e^{V_A/V_T}$$

Minority-carrier concentrations at the n-side and p-side depletion edges. Valid for low-level injection, meaning the injected minority density stays well below the majority density.

IDEAL DIODE EQUATION

$$I = I_0 \left(e^{V_A/V_T} - 1\right)$$

I flows from p to n through the diode. $V_A > 0$ is forward bias and $V_A < 0$ is reverse bias. When $|V_A| \gg V_T$ in reverse bias, $I \to -I_0$. Assumes low-level injection and no generation or recombination inside the depletion region.

DIODE EQUATION WITH IDEALITY FACTOR

$$I = I_0 \left(e^{V_A/(\eta V_T)} - 1\right), \qquad 1 \le \eta \le 2$$

$\eta \approx 1$ when diffusion current dominates. η approaches 2 when recombination in the depletion region dominates, which is typical of Si at low forward current. Use $\eta = 1$ unless the question gives another value.

REVERSE SATURATION CURRENT (LONG-BASE DIODE)

$$I_0 = qA \left(\frac{D_p\, p_{n0}}{L_p} + \frac{D_n\, n_{p0}}{L_n}\right)$$

D_p and D_n are the minority-carrier diffusion coefficients, with $D = \mu V_T$ (Einstein relation). $L_p = \sqrt{D_p \tau_p}$ and $L_n = \sqrt{D_n \tau_n}$ are the diffusion lengths. This form holds when each neutral region is much longer than its diffusion length. In a short-base diode, replace L_p and L_n by the neutral-region widths.

EQUILIBRIUM MINORITY-CARRIER CONCENTRATIONS

$$p_{n0} = \frac{n_i^2}{N_D}, \qquad n_{p0} = \frac{n_i^2}{N_A}$$

p_{n0} is the equilibrium hole concentration on the n-side and n_{p0} the equilibrium electron concentration on the p-side. From the mass-action law, for non-degenerate doping.

SMALL-SIGNAL (DYNAMIC) RESISTANCE IN FORWARD BIAS

$$r_d = \frac{dV_A}{dI} = \frac{\eta V_T}{I}$$

I is the DC forward current at the bias point, with $I \gg I_0$. For example, $r_d \approx 25.9\ \Omega$ at 1 mA with $\eta = 1$ at 300 K.

DIFFUSION CAPACITANCE (ONE-SIDED DIODE)

$$C_d = \frac{dQ}{dV_A} = \frac{\tau\, I}{\eta V_T}$$

Charge-control result for a one-sided long-base diode in forward bias ($I \gg I_0$). The stored charge is $Q = \tau I$, where τ is the minority-carrier lifetime on the lightly doped (injected) side. In a short-base diode, replace τ by the transit time $W_n^2/(2D_p)$, where W_n is the neutral n-region width. A full small-signal analysis of a long-base diode at low frequency gives half this value, $\tau I/(2\eta V_T)$; use whichever form the question specifies.

AVALANCHE BREAKDOWN VOLTAGE (ONE-SIDED ABRUPT JUNCTION)

$$V_{BR} \approx \frac{\epsilon_s E_{crit}^2}{2qN_B}$$

N_B is the doping of the lightly doped side. E_{crit} is the critical field for avalanche, a few $\times 10^5$ V/cm in Si, and it changes only weakly with doping. V_{bi} is neglected next to V_{BR}. So $V_{BR} \propto 1/N_B$: lighter doping gives a higher breakdown voltage.

ZENER PIECEWISE-LINEAR MODEL (IN BREAKDOWN)

$$V_Z = V_{Z0} + r_z I_Z$$

I_Z is the reverse current, taken positive, with $I_Z \geq I_{Z,min}$. V_{Z0} is the knee voltage and r_z the dynamic resistance. An ideal Zener has $r_z = 0$.

SHUNT REGULATOR: SERIES-RESISTOR LIMITS (IDEAL ZENER)

$$R_{max} = \frac{V_{S,min} - V_Z}{I_{L,max} + I_{Z,min}}, \qquad R_{min} = \frac{V_{S,max} - V_Z}{I_{L,min} + I_{Z,max}}$$

Supply V_S feeds the Zener in parallel with the load through a series resistor R. R_{max} keeps the Zener in regulation in the worst case (lowest supply, highest load current). R_{min} keeps the Zener current within its rating in the worst case (highest supply, lowest load current). Assumes $r_z = 0$.

IDEAL SCHOTTKY BARRIER HEIGHT

$$\phi_{Bn} = \phi_M - \chi, \qquad \phi_{Bp} = E_g - (\phi_M - \chi)$$

ϕ_M is the metal work function and χ the semiconductor's electron affinity. ϕ_{Bn} is the barrier to electrons on n-type material and ϕ_{Bp} the barrier to holes on p-type material. On n-type, the built-in potential of the contact is $\phi_{Bn} - (E_C - E_F)$, in volts.

SCHOTTKY DIODE THERMIONIC-EMISSION CURRENT

$$I = AA^{**}T^2 e^{-\phi_B/V_T}\left(e^{V_A/V_T} - 1\right)$$

A is the contact area, A^{**} the effective Richardson constant, and ϕ_B the barrier height in volts (numerically equal to its value in eV). The prefactor $AA^{**}T^2 e^{-\phi_B/V_T}$ is the saturation current, which replaces the diffusion-based I_0 of a p–n junction. For typical barrier heights it is several orders of magnitude larger than a comparable p–n junction's I_0.

The bipolar junction transistor as a device

COMMON-BASE CURRENT GAIN

$$\alpha = \gamma\,\alpha_T = \frac{I_{Cn}}{I_E}, \qquad I_C = \alpha I_E + I_{CBO}$$

This applies in active mode with no avalanche multiplication at the CBJ (multiplication factor $M = 1$). When I_{CBO} is negligible, $\alpha = I_C/I_E$. For a real device $\alpha < 1$, and it is close to 1.

COMMON-EMITTER CURRENT GAIN

$$\beta = \frac{\alpha}{1-\alpha}, \qquad \frac{1}{\beta} \approx (1-\gamma) + (1-\alpha_T)$$

When I_{CBO} is negligible, $\beta = I_C/I_B$. The second form holds when γ and α_T are both close to 1, and it shows how the two losses add. Because α is close to 1, β is very sensitive to small changes in α. Carry enough significant figures in $1-\alpha$ before dividing.

TERMINAL CURRENT RELATIONS (ACTIVE MODE, LEAKAGE NEGLECTED)

$$I_E = I_C + I_B, \qquad I_C = \alpha I_E = \beta I_B, \qquad I_E = (\beta+1) I_B, \qquad \alpha = \frac{\beta}{\beta+1}$$

The first relation is KCL for the whole device (currents taken into C and B and out of E for an npn). The others convert between α and β and give any one of I_E, I_B, I_C from another. A useful identity is $\beta + 1 = \dfrac{1}{1-\alpha}$.

LEAKAGE CURRENTS

$$I_C = \beta I_B + (\beta+1) I_{CBO}, \qquad I_{CEO} = (\beta+1)\, I_{CBO}$$

I_{CBO} is the collector current with the emitter open and the CBJ reverse-biased. I_{CEO} is the collector current with the base open. I_{CEO} is larger by a factor of $(\beta+1)$ because the leakage current, flowing into the base, is itself amplified. Both relations hold in active mode.

RECIPROCITY CONDITION

$$\alpha_F I_{ES} = \alpha_R I_{CS} \equiv I_S$$

This follows from the reciprocity of the device. It reduces the four Ebers–Moll parameters to three independent ones, and it defines the transport saturation current I_S.

ACTIVE-MODE REDUCTION

$$I_C \approx I_S\, e^{V_{BE}/V_T}, \qquad I_B \approx \frac{I_S}{\beta_F}\, e^{V_{BE}/V_T}, \qquad \beta_F = \frac{\alpha_F}{1-\alpha_F}$$

These hold when the EBJ is forward-biased with V_{BE} several times V_T, so the -1 is negligible, and $V_{BC} \le 0$, so the CBJ diode term contributes at most a small leakage. They follow from the Ebers–Moll equations using $I_B = I_E - I_C = (1-\alpha_F) I_{ES} e^{V_{BE}/V_T}$ and $I_S = \alpha_F I_{ES}$. This is the exponential law used for the active-mode I_C–V_{BE} characteristic.

EARLY EFFECT: COLLECTOR CURRENT

$$I_C(V_{CE}) = I_{C0}\left(1 + \frac{V_{CE}}{V_A}\right)$$

This first-order model holds in active mode at constant V_{BE}. $I_{C0} = I_S e^{V_{BE}/V_T}$ is the current extrapolated to $V_{CE} = 0$. V_A is the Early voltage. Extending the straight-line I_C–V_{CE} characteristic back to the V_{CE} axis gives a crossing at $V_{CE} = -V_A$.

SMALL-SIGNAL OUTPUT RESISTANCE

$$r_o = \left.\frac{\partial V_{CE}}{\partial I_C}\right|_{V_{BE}} = \frac{V_A + V_{CE}}{I_C} \approx \frac{V_A}{I_C}$$

It is evaluated at the DC operating point, in active mode. The middle expression follows exactly from the model above. The approximation V_A/I_C is the one normally used, and it holds when $V_A \gg V_{CE}$.

MOS capacitor, MOSFET and scaling

OXIDE CAPACITANCE PER UNIT AREA

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$$

$\varepsilon_{ox} = 3.9\varepsilon_0$ for SiO_2; t_{ox} is the oxide thickness. This is the parallel-plate result: it ignores polysilicon-gate depletion and the finite thickness of the inversion layer. Example: $t_{ox} = 10\ \text{nm}$ gives $C_{ox} = 3.45 \times 10^{-7}\ \text{F/cm}^2$.

BULK FERMI POTENTIAL (P-TYPE BODY)

$$\phi_F = \frac{kT}{q} \ln\left(\frac{N_A}{n_i}\right)$$

Valid for a non-degenerate, fully ionised body with $N_A \gg n_i$; $\phi_F > 0$ here. For an n-type body (PMOS) the magnitude is $|\phi_F| = V_T \ln(N_D/n_i)$ and ϕ_F is negative. Example: $N_A = 10^{16}\ \text{cm}^{-3}$ gives $\phi_F = 0.0259 \ln(6.67 \times 10^5) \approx 0.347\ \text{V}$.

GATE-BODY WORK-FUNCTION DIFFERENCE (P-TYPE BODY)

$$\phi_{ms} = \phi_m - \left(\chi + \frac{E_g}{2q} + \phi_F\right)$$

ϕ_m is the gate work function and χ the electron affinity of Si (about 4.05 V), both in volts. $E_g \approx 1.12\ \text{eV}$ for Si at 300 K, and the intrinsic level is taken at midgap. The bracket is the work function of the p-type body. For an n^+ polysilicon gate ($\phi_m \approx \chi$) this gives $\phi_{ms} \approx -\left(\frac{E_g}{2q} + \phi_F\right)$. For an n-type body, replace $+\phi_F$ by $-|\phi_F|$.

FLAT-BAND VOLTAGE

$$V_{FB} = \phi_{ms} - \frac{Q_{ox}}{C_{ox}}$$

Q_{ox} is the effective oxide charge per unit area (C/cm^2), treated as a sheet at the oxide-silicon interface. Charge located deeper in the oxide, closer to the gate, shifts V_{FB} less. Positive Q_{ox} makes V_{FB} more negative, and negative Q_{ox} makes it more positive.

MAXIMUM DEPLETION WIDTH

$$W_{dm} = \sqrt{\frac{4\varepsilon_{si}\phi_F}{qN_A}}$$

Depletion width at the onset of strong inversion ($\phi_s = 2\phi_F$), uniform doping, depletion approximation. In equilibrium (slow gate sweep), it barely grows beyond this, because the inversion charge supports any further gate charge. Under a fast ramp (deep depletion) it can exceed W_{dm}.

DEPLETION CHARGE AT THRESHOLD

$$Q_{d,max} = -qN_A W_{dm} = -\sqrt{4\varepsilon_{si} q N_A \phi_F}$$

Charge per unit area of the ionised acceptors in the depletion layer at $\phi_s = 2\phi_F$ and $V_{SB} = 0$. It is negative for a p-type body.

THRESHOLD VOLTAGE (NMOS, P-TYPE BODY, $V_{SB}=0$)

$$V_{TH0} = V_{FB} + 2\phi_F + \frac{\sqrt{4\varepsilon_{si} q N_A \phi_F}}{C_{ox}}$$

Uniform body doping, with Q_{ox} included through V_{FB}. Equivalently $V_{TH0} = V_{FB} + 2\phi_F + |Q_{d,max}|/C_{ox}$.

THRESHOLD VOLTAGE (PMOS, N-TYPE BODY, $V_{BS}=0$)

$$V_{TH0} = V_{FB} - 2|\phi_F| - \frac{\sqrt{4\varepsilon_{si} q N_D |\phi_F|}}{C_{ox}}$$

$|\phi_F| = V_T \ln(N_D/n_i)$. The depletion charge is positive (ionised donors) and the inversion layer is made of holes, so both terms add negatively. V_{FB} uses ϕ_{ms} for the n-type body.

BODY EFFECT (NMOS)

$$V_{TH} = V_{TH0} + \gamma\left(\sqrt{2\phi_F + V_{SB}} - \sqrt{2\phi_F}\right), \quad \gamma = \frac{\sqrt{2\varepsilon_{si} q N_A}}{C_{ox}}$$

$V_{SB} \geq 0$ is the source-to-body reverse bias, and γ is the body-effect coefficient (units $\sqrt{\text{V}}$). A larger V_{SB} widens the depletion region and raises V_{TH}. So in a stack of NMOS transistors with the body grounded, an upper device (source above ground) has a higher threshold. For PMOS the same form holds with magnitudes: $|V_{TH}|$ grows with $V_{BS} \geq 0$, with N_D and $|\phi_F|$ in place of N_A and ϕ_F.

THRESHOLD-ADJUST IMPLANT

$$\Delta V_{TH} = \frac{qD_I}{C_{ox}}$$

D_I is the implanted dose (ions/cm^2), assumed to sit as a thin sheet at the Si surface. An acceptor implant into an NMOS channel raises V_{TH}, and a donor implant lowers it.

INVERSION CHARGE ABOVE THRESHOLD

$$Q_n = -C_{ox}(V_{GS} - V_{TH})$$

Charge-sheet approximation, per unit area, for $V_{GS} > V_{TH}$ with $V_{DS} = 0$ (uniform channel). With $V_{DS} > 0$ the local channel voltage is subtracted from V_{GS}, which is where the square-law I-V model comes from.

MINIMUM (HIGH-FREQUENCY INVERSION) CAPACITANCE

$$\frac{1}{C_{min}} = \frac{1}{C_{ox}} + \frac{W_{dm}}{\varepsilon_{si}}$$

Isolated MOS capacitor, high test frequency, equilibrium (slow) DC sweep. W_{dm} is the maximum depletion width at $\phi_s = 2\phi_F$.

LINEAR (TRIODE) REGION

$$I_D = \mu_n C_{ox} \frac{W}{L}\left[(V_{GS} - V_{TH})V_{DS} - \frac{V_{DS}^2}{2}\right]$$

Valid for $V_{GS} > V_{TH}$ and $0 \le V_{DS} \le V_{GS} - V_{TH}$. μ_n is the electron mobility in the channel.

ON-RESISTANCE IN DEEP TRIODE

$$R_{on} = \frac{1}{\mu_n C_{ox} \dfrac{W}{L}(V_{GS} - V_{TH})}$$

For $V_{DS} \ll 2(V_{GS} - V_{TH})$ the V_{DS}^2 term is negligible, so the channel acts as a gate-controlled linear resistor.

PINCH-OFF (EDGE OF SATURATION)

$$V_{DS,sat} = V_{GS} - V_{TH}$$

In this model the inversion charge at the drain end falls to zero at this drain voltage. The triode expression reaches its maximum here, $I_{D,sat} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2$.

SATURATION REGION WITH CHANNEL-LENGTH MODULATION

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

Valid for $V_{GS} > V_{TH}$ and $V_{DS} \ge V_{GS} - V_{TH}$. λ (1/V) models channel-length modulation: as V_{DS} rises, the pinch-off point moves towards the source and the effective channel shortens. It is larger for shorter channels. With $\lambda = 0$, I_D does not depend on V_{DS} in saturation.

OUTPUT RESISTANCE IN SATURATION

$$r_o = \frac{1 + \lambda V_{DS}}{\lambda I_D} \approx \frac{1}{\lambda I_D}$$

Small-signal output resistance caused by channel-length modulation. The approximation holds when $\lambda V_{DS} \ll 1$.

TRANSCONDUCTANCE IN SATURATION

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

Square-law model in saturation, λ neglected. The three forms are equivalent; use whichever matches the given data. In the triode region, $g_m = \mu_n C_{ox}(W/L)V_{DS}$.

BODY TRANSCONDUCTANCE

$$g_{mb} = \frac{\gamma g_m}{2\sqrt{2\phi_F + V_{SB}}}$$

The change in I_D per unit change of body-to-source voltage, in saturation. It follows from differentiating the body-effect expression for V_{TH}.

UNITY-GAIN FREQUENCY (INTRINSIC, SATURATION)

$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})} \approx \frac{3\mu_n(V_{GS} - V_{TH})}{4\pi L^2}$$

In saturation the intrinsic gate-source capacitance is $C_{gs} \approx \frac{2}{3}WLC_{ox}$ and the intrinsic $C_{gd} \approx 0$. The approximate form neglects overlap and junction capacitances and uses the square-law g_m. f_T rises as $1/L^2$ when the channel is shortened.

SUBTHRESHOLD CURRENT

$$I_D \approx I_0 \exp\left(\frac{V_{GS} - V_{TH}}{n V_T}\right)\left[1 - \exp\left(-\frac{V_{DS}}{V_T}\right)\right]$$

Valid for $V_{GS} < V_{TH}$ (weak inversion, where the current is carried by diffusion). I_0 is a device-dependent current proportional to W/L. The bracket makes I_D practically independent of V_{DS} once V_{DS} exceeds a few V_T. $V_T = kT/q$ is the thermal voltage (25.9 mV at 300 K), not the threshold voltage.

SUBTHRESHOLD SLOPE FACTOR

$$n = 1 + \frac{C_{dep}}{C_{ox}}$$

Neglects interface-trap capacitance (traps add a further C_{it}/C_{ox}). $C_{dep} = \varepsilon_{si}/W_d$ is the depletion capacitance per unit area. A thinner oxide or a lighter body doping brings n closer to 1.

SUBTHRESHOLD SWING

$$S = n V_T \ln 10$$

The gate-voltage change needed for a tenfold change in subthreshold current (mV/decade). With $V_T = 25.9\ \text{mV}$, $V_T \ln 10 \approx 59.6\ \text{mV}$. Since $n \geq 1$, a conventional MOSFET at 300 K cannot switch more steeply than about 60 mV/decade. S is proportional to absolute temperature.

LEDs, photodiodes and solar cells

PHOTON ENERGY

$$E = h\nu = \frac{hc}{\lambda}$$

Holds for a photon of free-space wavelength λ. Numeric form: $E(\text{eV}) = \dfrac{1240}{\lambda(\text{nm})} = \dfrac{1.24}{\lambda(\mu\text{m})}$.

PHOTON FLUX

$$\Phi = \frac{P_{opt}}{h\nu} = \frac{P_{opt}\,\lambda}{hc}$$

Number of photons per second carried by monochromatic light of optical power P_{opt} (W). With $h\nu$ in eV, $\Phi = P_{opt}/(q\,h\nu[\text{eV}])$.

CUTOFF WAVELENGTH

$$\lambda_g = \frac{hc}{E_g} \approx \frac{1.24}{E_g(\text{eV})}\ \mu\text{m}$$

Band-to-band absorption occurs only for $\lambda \leq \lambda_g$ (i.e. $h\nu \geq E_g$). For $\lambda > \lambda_g$ there is no band-to-band absorption; the material is nearly transparent apart from weaker impurity and free-carrier absorption.

ABSORPTION WITH DEPTH

$$P(x) = P(0)\,e^{-\alpha x}$$

α is the absorption coefficient (cm^{-1}), which depends on wavelength; $1/\alpha$ is the penetration depth. The fraction of the light entering the material that is absorbed within a thickness W is $1 - e^{-\alpha W}$.

LED EMISSION (PEAK) WAVELENGTH

$$\lambda_{\text{emit}} \approx \frac{hc}{E_g} \approx \frac{1.24}{E_g(\text{eV})}\ \mu\text{m}$$

For band-to-band emission in a direct-gap material. The emitted photon energy is close to, and slightly above, E_g because the injected carriers are spread over a few kT above the band edges; this also gives the emission a finite spectral width.

INTERNAL QUANTUM EFFICIENCY

$$\eta_{int} = \frac{R_r}{R_r + R_{nr}} = \frac{\tau_{nr}}{\tau_r + \tau_{nr}}$$

Fraction of recombination events that emit a photon. R_r, R_{nr} are the radiative and non-radiative recombination rates; τ_r, τ_{nr} the corresponding lifetimes, with total lifetime $1/\tau = 1/\tau_r + 1/\tau_{nr}$.

LED OPTICAL OUTPUT POWER

$$P_{out} = \eta_{ext}\,\frac{I}{q}\,h\nu, \qquad \eta_{ext} = \eta_{inj}\,\eta_{int}\,\eta_{extr}$$

I is the forward current and $h\nu$ the photon energy (J). η_{ext} (external quantum efficiency) is photons leaving the device per electron passing through it; η_{inj} is the fraction of the current that recombines in the active region, and η_{extr} the fraction of generated photons that escape. With $h\nu$ in eV: $P_{out} = \eta_{ext}\,I\,h\nu[\mathrm{eV}]$ (W, with I in A).

CRITICAL ANGLE AT THE SEMICONDUCTOR-AIR SURFACE

$$\theta_c = \sin^{-1}\left(\frac{n_{air}}{n_s}\right) \approx \sin^{-1}\left(\frac{1}{n_s}\right)$$

Light striking the top surface at more than θ_c from the normal is totally internally reflected. For a typical III-V semiconductor ($n_s \approx 3.5$), $\theta_c \approx 17^\circ$, which is why only a small fraction of the generated light escapes a planar LED. At normal incidence the reflected fraction is $\left(\frac{n_s - 1}{n_s + 1}\right)^2$.

ILLUMINATED P-N JUNCTION (CURRENT INTO THE P TERMINAL POSITIVE)

$$I = I_0\left(e^{V/(nV_T)} - 1\right) - I_{ph}$$

V is positive for forward bias; I is the current flowing into the p terminal from the external circuit (the usual diode convention). I_0 is the reverse saturation (dark) current, n the ideality factor ($n = 1$ ideal) and $V_T \approx 25.9$ mV at 300 K. The photocurrent I_{ph} flows in the reverse direction and simply adds to the dark characteristic, which shifts the whole I-V curve down by I_{ph}. Assumes I_{ph} does not depend on V and neglects series and shunt resistance.

PHOTOCURRENT

$$I_{ph} = \eta\,q\,\frac{P_{opt}}{h\nu} = \frac{\eta\,q\,\lambda}{hc}\,P_{opt}$$

P_{opt} is the incident optical power (W) and η the quantum efficiency. Assumes no internal gain (each collected pair gives one electron of external current), i.e. not an avalanche photodiode.

QUANTUM EFFICIENCY

$$\eta = \frac{I_{ph}/q}{P_{opt}/h\nu}$$

Electron-hole pairs collected per second divided by photons incident per second; $0 \le \eta \le 1$ without internal gain. It is reduced by surface reflection, by light passing through without being absorbed, and by carriers recombining before they are collected. Ignoring collection losses, $\eta \approx (1 - R_f)\left(1 - e^{-\alpha W}\right)$, where R_f is the surface reflectance and W the absorbing (depletion) width.

RESPONSIVITY

$$R = \frac{I_{ph}}{P_{opt}} = \frac{\eta\,q\,\lambda}{hc} \approx \frac{\eta\,\lambda(\mu\mathrm{m})}{1.24}\ \mathrm{A/W}$$

Holds for $\lambda \le \lambda_g$; beyond the cutoff wavelength η, and so R, falls to nearly zero. At constant η the responsivity rises linearly with λ (a longer-wavelength photon carries less energy, so a watt contains more photons), then drops sharply near λ_g. The maximum possible value, at $\eta = 1$, is $\lambda(\mu\mathrm{m})/1.24$ A/W.

AVALANCHE PHOTODIODE (APD)

$$I = M\, I_{ph} = M\, \frac{\eta\, q\, \lambda}{hc}\, P_{opt}, \qquad R_{APD} = M\, \frac{\eta\, \lambda(\mu\mathrm{m})}{1.24}\ \mathrm{A/W}$$

An APD is reverse biased close to breakdown so that impact ionisation multiplies each photogenerated carrier; M is the average multiplication (gain) factor. Its responsivity can therefore exceed the $\eta = 1$ limit of an ordinary photodiode.

SOLAR CELL EQUATION (CURRENT DELIVERED TO THE LOAD POSITIVE)

$$I_{out} = I_L - I_0 \left(e^{V/(nV_T)} - 1 \right)$$

V is the terminal voltage (positive, since the cell forward biases itself), $I_{out} = -I$ is the current delivered to the external load, positive for $0 \le V \le V_{oc}$. I_0 is the reverse saturation (dark) current, n the ideality factor ($n = 1$ ideal) and $V_T = kT/q \approx 25.9$ mV at 300 K. Ideal model: series and shunt resistance neglected, I_L independent of V.

SHORT-CIRCUIT CURRENT

$$I_{sc} = I_{out}\big|_{V=0} = I_L$$

For a fixed spectrum, I_L is proportional to the incident optical power (photon flux), so I_{sc} is too. The ideal model is assumed (no series resistance).

OPEN-CIRCUIT VOLTAGE

$$V_{oc} = nV_T \ln\!\left(\frac{I_L}{I_0} + 1 \right) \approx nV_T \ln\!\left(\frac{I_L}{I_0} \right) \ \text{for } I_L \gg I_0$$

Obtained by setting $I_{out} = 0$. V_{oc} grows only logarithmically with light intensity: multiplying the intensity by k raises V_{oc} by $nV_T \ln k$. V_{oc} falls as temperature rises, because I_0 (proportional to n_i^2) rises steeply with temperature.

MAXIMUM POWER POINT (IDEAL CELL)

$$\left(1 + \frac{V_{mp}}{nV_T} \right) e^{V_{mp}/(nV_T)} = 1 + \frac{I_L}{I_0}, \qquad I_{mp} = I_L - I_0 \left(e^{V_{mp}/(nV_T)} - 1 \right)$$

From $\dfrac{dP}{dV} = 0$ with $P = VI_{out}$. The maximum power point lies on the curve between $(0, I_{sc})$ and $(V_{oc}, 0)$, with $V_{mp} < V_{oc}$ and $I_{mp} < I_{sc}$.

FILL FACTOR

$$FF = \frac{V_{mp}\, I_{mp}}{V_{oc}\, I_{sc}}$$

Ratio of the maximum-power rectangle to the rectangle $V_{oc} \times I_{sc}$. Always $FF < 1$, since $V_{mp} < V_{oc}$ and $I_{mp} < I_{sc}$. It is reduced by series resistance and by low shunt resistance.

CONVERSION EFFICIENCY

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{mp} I_{mp}}{P_{in}} = \frac{FF \cdot V_{oc} \cdot I_{sc}}{P_{in}}$$

P_{in} is the total optical power incident on the cell, under the same illumination at which I_{sc} and V_{oc} are measured.

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