EE Formula Sheet

§1 - The Crystal Structure of Solids

Miller Index

1. Identify the intercepts: Locate the points where the plane intersects the crystallographic axes (usually denoted as a, b, and c).
2. Convert to fractional coordinates: Express these intercepts as fractions of the unit cell dimensions (a, b, c). To do this, divide each intercept by the respective unit cell dimension. If an intercept does not intersect the corresponding axis, use ∞ as the fraction.
3. Take reciprocals: Invert the fractional intercepts to obtain the reciprocal fractions.
4. Simplify the ratios: If any of the reciprocals are not integers, multiply all the indices by the smallest integer that makes them all whole numbers while maintaining the ratio. This ensures that the Miller indices are in the simplest form.
5. Enclose in parentheses: Write the indices as (hkl), where h, k, and l are the integers obtained after simplification. These are the Miller indices that represent the crystallographic plane.
6. Optional: If the plane is parallel to an axis (intercepts at infinity), write the corresponding Miller index as 0. For example, if a plane is parallel to the a-axis and intercepts the b and c-axes at infinity, its Miller indices would be $(0bc)$.

Principles of Quantum Mechanics

1. Superposition Principle: Quantum systems can exist in a linear combination of multiple states simultaneously, described by a wavefunction.
2. Wave-Particle Duality: Particles, such as electrons and photons, exhibit both wave-like and particle-like properties.
3. Uncertainty Principle: There is a fundamental limit to the precision with which certain pairs of properties, such as position and momentum, can be simultaneously known.
4. Quantum States and Operators: Quantum states are described by wavefunctions, and operators represent physical observables and transformations.
5. Measurement and Collapse: Measurement of a quantum system collapses its wavefunction to one of its possible states, with probabilities determined by the square of the amplitude of the wavefunction.
6. Quantum Entanglement: Entangled particles exhibit correlations that cannot be explained by classical physics, even when separated by large distances.
7. Quantum Tunneling: Particles can penetrate energy barriers that classical physics predicts they should not be able to cross.
8. Quantum Interference: Quantum systems can exhibit interference patterns when multiple pathways are available.
9. Quantum Information: Quantum mechanics plays a crucial role in the field of quantum computing and quantum cryptography, offering advantages in information processing and security.

Broglie Wavelength

Convert energy from eV to J:

$$E = 1.0\,\text{eV} = 1.60219 \times 10^{-19}\,\text{J}$$

Calculate momentum of the proton or electron:

$$p_{\text{proton}} = \sqrt{2 \cdot m_{\text{proton}} \cdot E}$$

Where: p_{proton} = momentum of the proton, m_{proton} = mass of the proton ($\approx 1.6726219 \times 10^{-27}$ kg), E = kinetic energy (in Joules)

$$p_{\text{electron}} = \sqrt{2 \cdot m_{\text{electron}} \cdot E}$$

Where: p_{electron} = momentum of the electron, m_{electron} = mass of the electron ($\approx 9.10938356 \times 10^{-31}$ kg), E = kinetic energy (in Joules)
Calculate the de Broglie wavelength:

$$\lambda = \frac{h}{p}$$

Where: λ = de Broglie wavelength, h = Planck's constant ($6.62607015 \times 10^{-34}$ m² kg/s)

Energy

The energy (E) of a photon is given by $E = h\nu$, where h is Planck's constant and ν is the frequency.
The frequency (ν) of a photon is inversely proportional to its wavelength (λ) and can be determined by the equation $\nu = \frac{c}{\lambda}$, where c is the speed of light.

Constants

$$q = 1.602 \times 10^{-19}\ \text{C}$$
$$m_e = 9.109 \times 10^{-31}\ \text{kg}$$
$$h = 6.626 \times 10^{-34}\ \text{J} \cdot \text{s}$$
$$k = 1.381 \times 10^{-23}\ \text{J/K}$$
$$\varepsilon_0 = 8.854 \times 10^{-12}\ \text{C}^2/(\text{N} \cdot \text{m}^2)$$
$$c = 3.00 \times 10^{8}\ \text{m/s}$$
$$e \approx 1.6 \times 10^{-19}\ \text{C}$$
$$kT \approx 0.026 \text{eV} \text{at} T = 300\text{K}$$

Formulae

$kT_{temp} = 0.026(\frac{temp}{300})$, kT at a temperature temp
$\sigma = en\mu_n + ep\mu_p$, Conduction
$n_i^2 = n_0 p_0$, concentration at equilibrium
$n_i^2 = n_c n_v e^{-E_g/kT}$,
$n_i^2 \propto T^3 e^{-E_g/kT}$, proportionality ratio
$n_i^2 at500 = (\frac{500}{300})^3 e^{-E_g/kTat500} e^{E_g/kTat300}$, proportional temp
$E = \frac{hc}{\lambda}$, energy of photon
$E_g = E_c - E_v$, Energy band gap
$f(E) = \frac{1}{1+e^{\frac{E-E_f}{kT}}}$, Fermi-Dirac Distribution Function
$n = N_c \cdot e^{-\frac{E_c - E_f}{kT}}$, Electron carrier concentration
$p = N_v \cdot e^{-\frac{E_f - E_v}{kT}}$, Hole carrier concentration
$J_d = q \cdot n \cdot \mu_n \cdot E$, Drift Current
$J_n = q \cdot D_n \cdot \frac{dn}{dx}$, Diffusion Current
$E_g = E_c - E_v$, Energy-Band Gap (Eg)

$\frac{1}{m^*} = \frac{1}{m_l} + \frac{1}{m_t}$, Electron and Hole Effective Mass
$q = 1.602 \times 10^{-19}$ C, Charge of an Electron
$n = N_c \cdot e^{-\frac{E_c - E_f}{kT}}$, Electron Carrier Concentration
$p = N_v \cdot e^{-\frac{E_f - E_v}{kT}}$, Hole Carrier Concentration
$J_n = q \cdot n \cdot \mu_n \cdot E$, Drift Current Density for Electrons
$J_p = q \cdot p \cdot \mu_p \cdot E$, Drift Current Density for Holes
$J_n = q \cdot D_n \cdot \frac{dn}{dx}$, Diffusion Current Density for Electrons
$J_p = q \cdot D_p \cdot \frac{dp}{dx}$, Diffusion Current Density for Holes
$N_c = 2\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2}$, Density of States in the Conduction Band (Nc)
$N_v = 2\left(\frac{2\pi m_h kT}{h^2}\right)^{3/2}$, Density of States in the Valence Band (Nv)
$P_0 = n_i e^{\frac{E_{fi} - E_f}{kT}}$
$P_0 = \frac{N_A - N_D}{2} + \sqrt{(\frac{N_A - N_D}{2})^2 + n_i^2}$
$N_0 = \frac{N_D - N_A}{2} + \sqrt{(\frac{N_D - N_A}{2})^2 + n_i^2}$
$f_F(E) = \frac{1}{1+e^{\frac{E-E_f}{kT}}}$, Fermi-Dirac Distribution Function
$f_F(E) = e^{\frac{-(E-E_f)}{kT}})$, Boltzman Approximation when $E - E_F >> kT$
$\mu_n = \frac{q \cdot \tau_n}{m^*}$, Electron Mobility
$\mu_p = \frac{q \cdot \tau_p}{m^*}$, Hole Mobility
$G = \alpha \cdot I$, Generation Rate of Electron-Hole Pairs
$R = B \cdot np - A \cdot n_i^2$, Recombination Rate
$\frac{\partial n}{\partial t} + \nabla \cdot \mathbf{J}_n = G - R$, Continuity Equation for Electron Current
$\frac{\partial p}{\partial t} - \nabla \cdot \mathbf{J}_p = G - R$, Continuity Equation for Hole Current
$P_0 + N_D = n_0 + N_A$, Charge neutrality
$J_{drf} = en\mu_n E + ep\mu_p E = \sigma E$, Total Drift
$I = AJ_{drf}$, Current
$E = Volt/Len$, Electric Field
$V_{dn} = \mu_n E$, Drift velocity for electrons
$V_{dp} = \mu_p E$, Drift velocity for holes

§1.2 - The PN Junction

Notes

Common Source: Input connected to gate, output connected to drain.
Common Drain (Source Follower): Input connected to gate, output connected to source.
Common Gate: Input connected to source, output connected to drain.
When $N_A >> N_D$, the semiconductor is p-type.
When $N_D >> N_A$, the semiconductor is n-type.

Transistor formulas

$I_C = \beta \cdot I_B$, Conduction Parameter
$I_B = \frac{I_E}{\beta+1}$,
$\alpha = \frac{I_C}{I_E}$, Current Ratio
$I_C = I_E - I_B$, Kirchhoff's Current Law
$V_{CE} = V_{BE} + V_{CB}$, Voltage Relationships
$I_C = I_{C0}\left(e^{\frac{V_{BE}}{V_T}} - 1\right)$, BJT Current Equation
$I = I_0 \cdot \left(e^{\frac{V}{n \cdot V_T}} - 1\right)$, Schottky Diode Equation
$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2$, MOSFET Drain Current Equation
$I_D = \mu_n C_{ox}\frac{W}{L}\left[(V_{GS} - V_{TH})V_{DS} - \frac{V_{DS}^2}{2}\right]$, MOSFET Drain Current Equation (Triode Region)
$g_m = \sqrt{2\mu_n C_{ox}\frac{W}{L} I_D}$, Transconductance Parameter
$A_v = -g_m \cdot R_D$, Voltage Gain Formula

EE General Formulae

$rms = \frac{1}{\sqrt{2}}$,
$V = I \cdot R$, Ohm's law.
$P = V \cdot I$, DC Power.
$P = V \cdot I \cdot \cos(\theta)$, AC power.
$E = P \cdot t$, Energy.
$C = \frac{Q}{V}$, Capacitance.
$V = L \cdot \frac{di}{dt}$, Inductance.
$\tau = R \cdot C$, Time constant to reach 63.2% of capacitors final voltage.
$\tau = \frac{L}{R}$, Time constant to reach 63.2% of inductors final value.
$\frac{N_1}{N_2} = \frac{V_1}{V_2}$, Transformer turns ratio.
$V_{\text{peak}} = \sqrt{2} \cdot V_{\text{rms}}$, Peak AC Voltage.
$V_{\text{rms}} = \frac{V_{\text{peak}}}{\sqrt{2}}$, RMS AC Voltage.
$V_{\text{avg}} = \frac{1}{T}\int_0^T V(t)\,dt$, RMS AC Voltage.
$V_{\text{out}} = V_{\text{in}} \cdot \frac{R_2}{R_1+R_2}$, voltage divider.
$R_{\text{eq}} = R_1 + R_2 + \ldots + R_n$, series resistors.
$\frac{1}{R_{\text{eq}}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}$, Parallel resistors.
$\frac{1}{C_{\text{eq}}} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_n}$, Series capacitors.
$C_{\text{eq}} = C_1 + C_2 + \ldots + C_n$, parallel capacitors.

Convert Polar to Rectangular

$$x = r\cos\theta$$
$$y = r\sin\theta$$

Exact Slope of a Tangent Line

$$\frac{dy}{dx} = \frac{dy/dt}{dx/dt}$$

Basic integration Rules

$\int kf(u)du = k\int f(u)du + C$,
$\int[f(u) \pm g(u)]du = \int f(u)du \pm \int g(u)du$, $\int du = u + C$,
$\int u^n du = \frac{u^{n+1}}{n+1} + C, n \neq -1$, $\int \frac{du}{u} = \ln|u| + C$,
$\int \frac{u}{du} = \frac{u^2}{2} + C$, $\int e^u du = e^u + C$,$\int e^{4u} = \frac{e^{4u}}{4} + C$,
$\int a^u du = \left(\frac{1}{\ln a}\right)a^u + C$,

Some Integrals

$\int \sin u du = -\cos u + C$, $\int \cos u du = \sin u + C$,
$\int \tan u du = -\ln|\cos u| + C$, $\int \cot u du = \ln|\sin u| + C$,
$\int \sec u du = \ln|\sec u + \tan u| + C$,
$\int \csc u du = -\ln|\csc u + \cot u| + C$, $\int \sec^2 u du = \tan u + C$,
$\int \csc^2 u du = -\cot u + C$, $\int \sec u \tan u du = \sec u + C$,
$\int \csc u \cot u du = -\csc u + C$, $\int \frac{du}{\sqrt{a^2-u^2}} = \arcsin\frac{u}{a} + C$,
$\int \frac{du}{a^2+u^2} = \frac{1}{a}\arctan\frac{u}{a} + C$, $\int \frac{du}{u\sqrt{u^2-a^2}} = \frac{1}{a}\text{arcsec}\frac{|u|}{a} + C$,
$\int \sin 3x = -\frac{1}{3}\cos 3x$, $\int e^{-4x} = \frac{e^{-4x}}{-4}$
$\int kdx = kx + C$, $\int xdx = \frac{1}{2}x^2 + C$, $\int x^2 dx = \frac{1}{3}x^3 + C$,
$\int \frac{1}{x}dx = \ln|x| + C$, $\int e^x dx = e^x + C$,$\int k^u du = \frac{k^u}{\ln u} + C$,
$\int \ln x dx = x\ln x - x + C$, $\int \cos x dx = \sin x + C$,
$\int \sin x dx = -\cos x + C$, $\int \sec^2 x dx = \tan x + C$,
$\int x^n dx = \frac{x^{n+1}}{n+1} + C$, $\int \tan x = -\ln(\cos x) + C$,

Integration by Parts

$$\int udv = uv - \int vdu$$

Some Identities

$\sin 2x = 2\sin x\cos x$

Pythagorean:

$\sin^2 x + \cos^2 x = 1$, $1 + \tan^2 x = \sec^2 x$, $1 + cot^2 x = \csc^2 x$

Reciprocal:

$\sin x = \frac{1}{\csc x}$, $\cos x = \frac{1}{\sec x}$, $\tan x = \frac{\sin x}{\cos x} = \frac{1}{\cot x}$
$\csc x = \frac{1}{\sin x}$, $\sec x = \frac{1}{\cos x}$, $\cot x = \frac{\cos x}{\sin x} = \frac{1}{\tan x}$

Half Angle:

$\sin^2 x = \frac{1}{2}(1 - \cos 2x)$, $\cos^2 x = \frac{1}{2}(1 + \cos 2x)$

Additional Notes:

$\ln(x * y) = \ln(x) + \ln(y)$, $\ln(x/y) = \ln(x) - \ln(y)$
$\ln x^a = a\ln x$, $\tan\theta = \frac{\sin\theta}{\cos\theta}$
$ax^2 + bx + c = 0$, $x = \frac{-b\pm\sqrt{b^2-4ac}}{2a}$
$\ln a = c \equiv e^c = a$
$\sqrt[n]{a} = a^{\frac{1}{n}}$, $a^{-n} = \frac{1}{a^n}$, $\sqrt[n]{a^m} = a^{\frac{m}{n}}$, $a^0 = 1$, $(a^m)^n = a^{mn}$,
$a^m * a^n = a^{m+n}$, $\frac{a^m}{a^n} = a^{m-n}$, Rewrite $\sqrt{5x}$ as $\sqrt{5}\sqrt{x}$,

Some Derivatives:

$\frac{d}{du}\sin u = (\cos u)u'$, $\frac{d}{du}\cos u = -(\sin u)u'$,
$\frac{d}{du}\tan u = (\sec^2 u)u'$, $\frac{d}{du}\cot u = -(\csc^2 u)u'$,
$\frac{d}{du}\sec u = (\sec u\tan u)u'$, $\frac{d}{du}\csc u = -(\csc u\cot u)u'$,
$\frac{d}{du}\arcsin u = \frac{u'}{\sqrt{1-u^2}}$, $\frac{d}{du}\arccos u = \frac{-u'}{\sqrt{1-u^2}}$,
$\frac{d}{du}\arctan u = \frac{u'}{1+u^2}$, $\frac{d}{du}\text{arccot}\, u = \frac{-u'}{1+u^2}$,
$\frac{d}{du}\text{arcsec}\, u = \frac{u'}{|u|\sqrt{u^2-1}}$, $\frac{d}{du}\text{arccsc}\, u = \frac{-u'}{|u|\sqrt{u^2-1}}$
$\frac{d}{du}[\ln u] = \frac{1}{u}u'$, $\frac{d}{dx}[e^{-x}] = -e^{-x}$, $e^{\ln a} = a$
$\frac{d}{du}[\sqrt{u}] = \frac{u'}{2\sqrt{u}}$, $e^{3x} = 3e^{3x}$, $\frac{d}{dx}[x] = 1$, $\frac{d}{dx}[c] = 0$,
$\frac{d}{du}[\frac{1}{u}] = \frac{1}{u^2}$, $\frac{du}{u} = \ln|u|$,