THE UNIVERSITY OF WESTERN AUSTRALIA

Electrical, Electronic & Computer Engineering

SEMESTER 1, 2021 EXAMINATIONS

ENSC3014
ELECTRONIC MATERIALS AND DEVICES -ATTACHMENT

FAMILY NAME:________________ GIVEN NAMES:________________

STUDENT ID: | | | | | | | | | SIGNATURE: ________________

This attachment contains: 15 pages (including this page)

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CONSTANTS	
Charge on an electron, q, or e	1.60×10^{-19} C
Boltzmann's constant, k	1.38×10^{-23} JK^{-1}
Speed of light in free space, c	3.00×10^{8} ms^{-1}
Plank's constant, h	6.62×10^{-34} Js
Reduced Plank's constant,$\hbar$	$\frac{h}{2\pi}$
Mass of an electron	9.11×10^{-31} kg
Mass of a proton or a neutron	1.67×10^{-27} kg
Permittivity of free space	8.85×10^{-14} Fcm^{-1}

PROPERTIES			
Material	Si	GaAs	SiO_2
Intrinsic carrier concentration, n_i	1.45×10^{10} cm^{-3}	1.79×10^{6} cm^{-3}	
Electron mobility, μ_e	1350 cm^{2}V^{-1}s^{-1}	8500 cm^{2}V^{-1}s^{-1}	
Hole mobility, μ_h	480 cm^{2}V^{-1}s^{-1}	400 cm^{2}V^{-1}s^{-1}	
Relative Permittivity, ε_r	11.7	13.1	3.9
Energy band gap, E_G	1.12 eV	1.42 eV	8.9 eV
Effective density of states in conduction band, N_C	4.3×10^{19} cm^{-3}	4.7×10^{17} cm^{-3}	
Effective density of states in valence band, N_V	2.5×10^{19} cm^{-3}	7×10^{18} cm^{-3}	

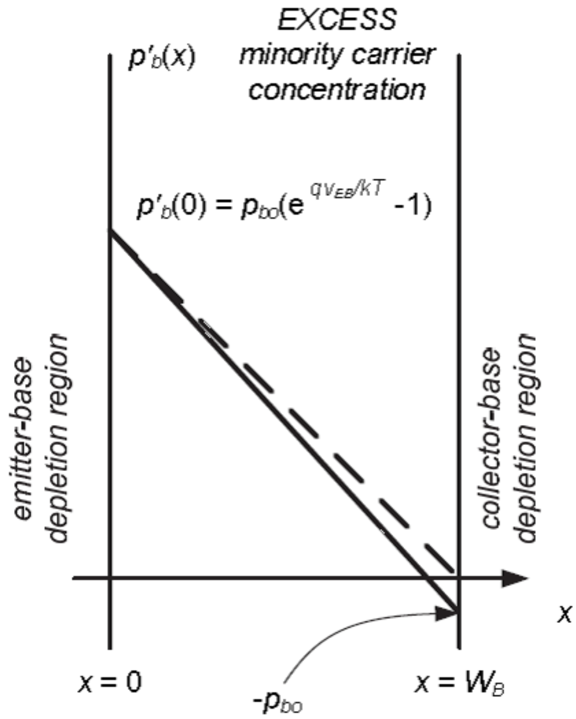
QUANTUM MECHANICS	
Shroedinger's wave equations in one dimension	$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\Psi}{\partial x^2} + V\Psi$ (full) $\Psi = \psi(x)\phi(t)$ (separable solutions) $E\psi = -\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} + V\psi$ (time-independent) $\phi(t) = e^{-j\frac{E}{\hbar}t}$ (time-dependent part)
De-Broglie's wave-particle duality	$p = \frac{h}{\lambda}$
Energy of a photon	$E = h\nu$, where ν is the frequency of light

Effective mass	$m^* = \hbar^2 / \left(\frac{d^2E}{dk^2}\right)$
The Fermi Level in a semiconductor	$E_F - E_V = \frac{E_G}{2} + \frac{3}{4}kT \ln\left(\frac{m_h^*}{m_e^*}\right) + \frac{1}{2}kT \ln\left(\frac{n}{p}\right)$
Maxwell-Boltzmann approximation of carrier concentrations	$n = N_C \exp\left(-\frac{E_C - E_F}{kT}\right)$ $p = N_V \exp\left(-\frac{E_F - E_V}{kT}\right)$ where, $N_C = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}}$ $N_V = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}}$
Alternative Maxwell-Boltzmann expressions of carrier concentrations	$n = n_i \exp\left(\frac{E_F - E_i}{kT}\right)$ $p = n_i \exp\left(\frac{E_i - E_F}{kT}\right)$
Thermal equilibrium condition	$p(x)n(x) = n_i^2$

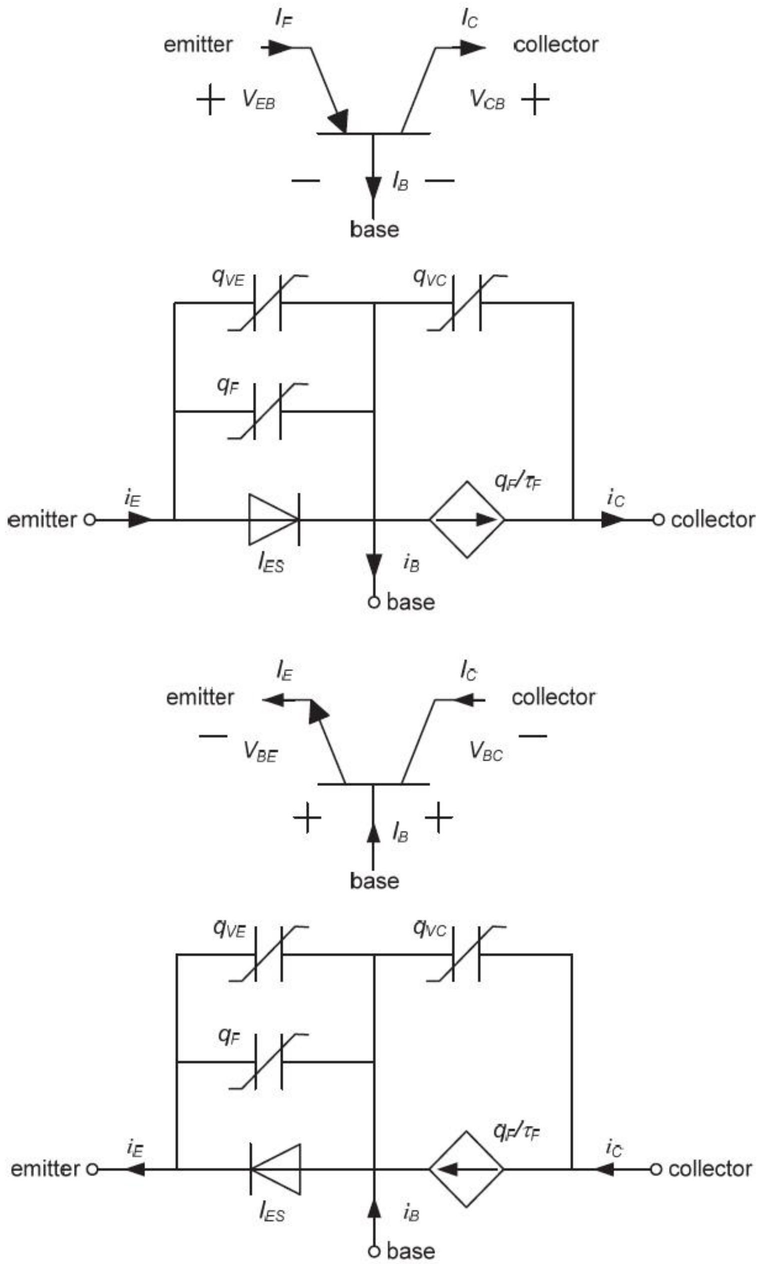
Conductivity, resistivity and resistance	$\sigma = nq\mu_n + pq\mu_p$ $\rho = \frac{1}{\sigma}$ $R = \frac{\rho l}{A}$
Current Density	$J_n = nq\mu_n\mathcal{E} + qD_n\frac{dn}{dx}$ $J_p = pq\mu_p\mathcal{E} - qD_p\frac{dp}{dx}$
Continuity equations	$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \cdot J_n + G_n - R_n$ $\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla \cdot J_p + G_p - R_p$
Net rate of recombination	$U = R - G_{th}$
Trap assisted (Shockley-Read-Hall) net recombination rate	$U = \sigma v_{th} N_t \frac{pn - n_i^2}{p + n + 2n_i cosh\left(\frac{E_F - E_i}{kT}\right)}$ where σ is the capture cross-section and v_{th} is the average thermal energy of carriers.
Approximate net rate of recombination in neutral regions	$U = R - G_{th}$ $= \frac{p_n - p_{n0}}{\tau_p}$ n-type material $= \frac{n_p - n_{p0}}{\tau_n}$ p-type material

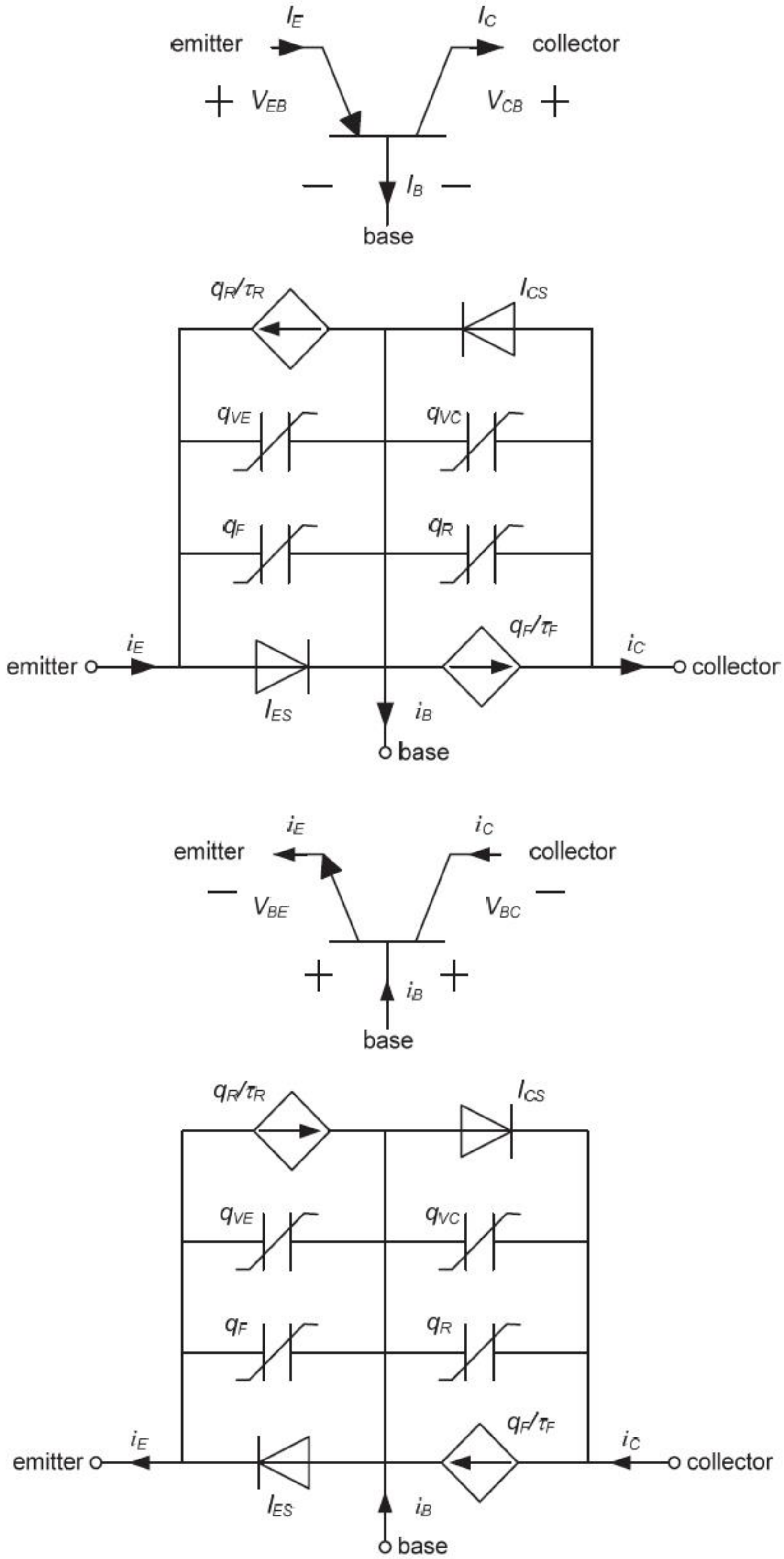
Poisson's Equation	$\frac{d\mathcal{E}}{dx} = \frac{\rho}{\varepsilon_r \varepsilon_0}$
Relationship between electric field and electrostatic potential	$\mathcal{E} = -\frac{d\psi}{dx}$
Relationship between electrostatic potential and band structure	$\psi = -\frac{E_i}{q}$

Built in potential of pn junction	$V_{bi} = \frac{1}{q}\left(E_{Fn} - E_{Fp}\right) \approx \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)$
Depletion region widths (abrupt junctions)	$x_n = \sqrt{\frac{2\varepsilon_r\varepsilon_0}{qN_D}\left(\frac{N_A}{N_A+N_D}\right)(V_{bi}-V_J)}$ $x_p = \sqrt{\frac{2\varepsilon_r\varepsilon_0}{qN_A}\left(\frac{N_D}{N_A+N_D}\right)(V_{bi}-V_J)}$ $W = x_n + x_p = \sqrt{\frac{2\varepsilon_r\varepsilon_0}{q}\left(\frac{N_A+N_D}{N_A N_D}\right)(V_{bi}-V_J)}$
Diode depletion region differential capacitance per unit area	$C = \frac{dQ_J}{dV_J} = \frac{\varepsilon_r\varepsilon_0}{W} = \frac{\varepsilon_r\varepsilon_0}{\sqrt{\frac{2\varepsilon_r\varepsilon_0}{q}\left(\frac{N_A+N_D}{N_A N_D}\right)(V_{bi}-V_J)}}$
Approximate max net rate of generation in an depletion region (works for both forward bias and reverse bias)	$U_{MAX} = \frac{n_i}{2\tau_0}\left(\exp\left(\frac{qV_J}{2kT}\right)-1\right)$ where, $\tau_0 = \frac{1}{\sigma v_{th} N_t}$, is the minority carrier lifetime
pn junction diffusion currents (works for both forward and reverse bias). Replace L_p or L_n by W for a short-base diode, where W is the length of the neutral region between the depletion region to the contact.	$I_{diff,p} = qD_p\frac{p_{n0}}{L_p}A_J\left(\exp\left(\frac{qV_J}{kT}\right)-1\right)$ $I_{diff,n} = qD_n\frac{n_{p0}}{L_n}A_J\left(\exp\left(\frac{qV_J}{kT}\right)-1\right)$ where, $L_p = \sqrt{D_p\tau_p}$ (in neutral n-region) $L_n = \sqrt{D_n\tau_n}$ (in neutral p-region)
pn junction generation/recombination currents in depletion region (works for both forward and reverse bias.)	$I_{rec/gen} = qA_J W\frac{n_i}{2\tau_0}\left(\exp\left(\frac{qV_J}{2kT}\right)-1\right)$
Total pn junction currents	$I = I_{rec/gen} + I_{diff,p} + I_{diff,n}$
Quasi-static approximation for carrier concentrations at the edge of a depletion region in a pn junction	$p_n(x=0) = p_{n0}\exp\left(\frac{qV_J}{kT}\right)$ $n_p(x=-W) = n_{p0}\exp\left(\frac{qV_J}{kT}\right)$

Excess minority carrier concentration in the base in forward active.	
Excess minority carrier charge in the base in forward active.	$q_F = Q_{F0}\left(\exp\left(\frac{qV_{EB}}{kT}\right) - 1\right)$ where, $Q_{F0} = \frac{qA_J W_B p_{b0}}{2}$
Static collector current in forward active.	$I_C \approx qA_J D_b \frac{p'_b(0)}{W_B}$ $= I_1\left(\exp\left(\frac{qV_{EB}}{kT}\right) - 1\right)$ $= \frac{q_F}{\tau_F}$ where, $I_1 = \frac{qA_J D_b p_{b0}}{W_B}$ $\tau_F = \frac{(W_B)^2}{2D_b}$

Static base current in forward active	$I_B = I_{BA} + I_{BB}$ $= \frac{qA_J W_B}{2\tau_b} p_b'(0) + \frac{qA_J D_e}{W_E}\left(\frac{n_{e0}}{p_{b0}}\right) p_b'(0)$ $= \frac{q_F}{\tau_{BF}}$ where, $\tau_{BF} = \frac{1}{\frac{1}{\tau_b} + \frac{2D_e n_{e0}}{W_B W_E p_{b0}}}$
Static base current as a fraction of the static collector current in forward active.	$I_B = \delta I_C$ where, $\delta = \frac{\frac{W_B}{2\tau_B} + \frac{D_e}{W_E}\left(\frac{n_{e0}}{p_{b0}}\right)}{D_b/W_b}$ (called the base defect)
Static emitter current in forward active	$I_E = I_C + I_B = (1+\delta)I_C$
Charge control equations in forward active	$i_C = \frac{q_F}{\tau_F} - \frac{dq_{VC}}{dt}$ $i_B = \frac{dq_F}{dt} + \frac{dq_{VE}}{dt} + \frac{dq_{VC}}{dt} + \frac{q_F}{\tau_{BF}}$ $i_E = \frac{dq_F}{dt} + \frac{dq_{VE}}{dt} + \frac{q_F}{\tau_{BF}} + \frac{q_F}{\tau_F}$

<table>
<tr><td>Charge control model in forward active</td><td>
</td></tr>
<tr><td>Complete charge control model equations</td><td>$i_C = \frac{q_F}{\tau_F} - \frac{dq_R}{dt} - q_R\left(\frac{1}{\tau_{BR}} + \frac{1}{\tau_R}\right) - \frac{dq_{VC}}{dt}$
$i_B = \frac{dq_F}{dt} + \frac{q_F}{\tau_{BF}} + \frac{dq_R}{dt} + \frac{q_R}{\tau_{BF}} + \frac{dq_{VE}}{dt} + \frac{dq_{VC}}{dt} + \frac{q_F}{\tau_{BF}}$
$i_E = -\frac{q_R}{\tau_R} + \frac{dq_F}{dt} + q_F\left(\frac{1}{\tau_{BF}} + \frac{1}{\tau_F}\right) + \frac{dq_{VE}}{dt}$
where,
$q_R = Q_{R0}\left(e^{\frac{qV_{CB}}{kT}} - 1\right)$</td></tr>
</table>

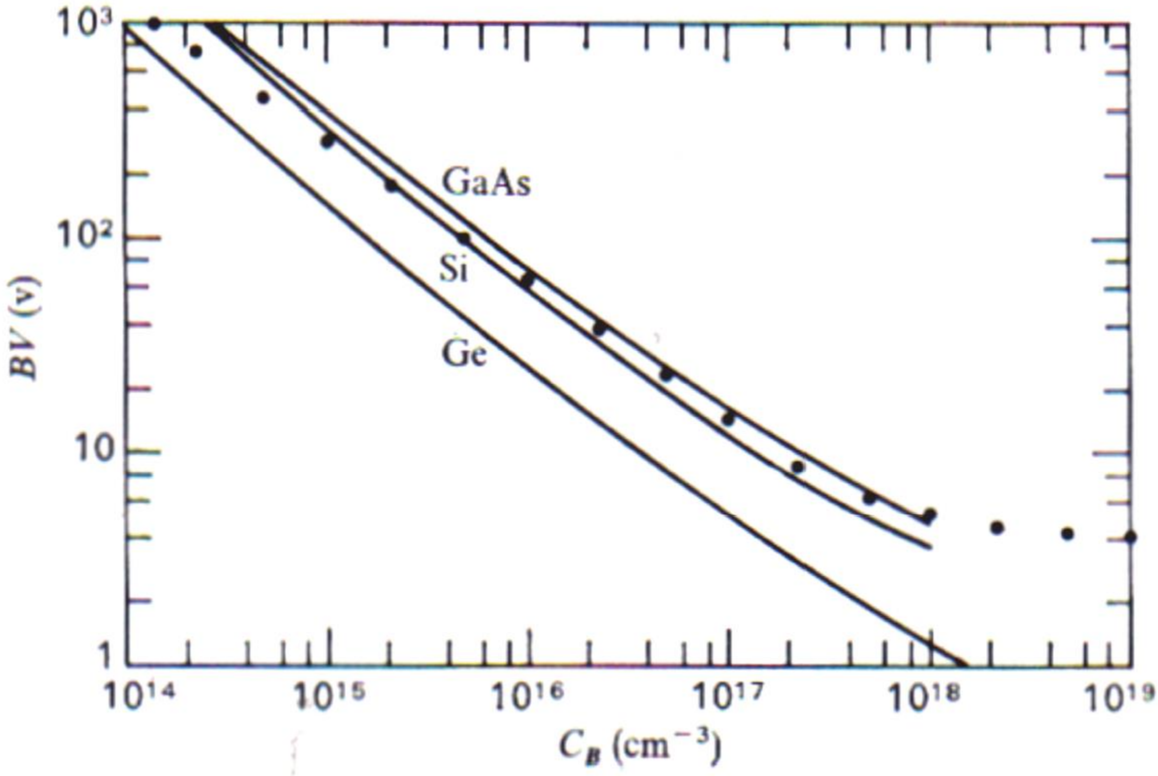
Complete charge-control model (valid in all regions of operation)	

Ideal n-channel MOSFET drain current	Triode: $I_D = \frac{Z}{L}\mu_n C_{ox}\left[\left(V_G - V_T\right)V_D - \frac{1}{2}{V_D}^2\right]$ Saturation: $I_{Dsat} = \frac{1}{2}\frac{Z}{L}\mu_n C_{ox}\left(V_G - V_T\right)^2$
Fermi Potential	p-type silicon: $\phi_p = \frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right)$ n-type silicon: $\phi_n = \frac{kT}{q}\ln\left(\frac{N_D}{n_i}\right)$
MOS Depletion width	p-type silicon: $W_d = \left(\frac{2\varepsilon_S\phi_s}{qN_A}\right)^{\frac{1}{2}}$ n-type silicon: $W_d = \left(\frac{2\varepsilon_S\phi_s}{qN_D}\right)^{\frac{1}{2}}$
MOS silicon charge	$V_G - V_{FB} = -\frac{Q_s}{C_{ox}} + \phi_s$
MOS voltage relationship	$V_G = \phi_{MS} + V_{ox} + \phi_s$
MOS inversion layer charge (p-type)	$Q_n = -\left(V_G - V_T\right)C_{ox}$
Ideal MOS saturation voltage	$V_{Dsat} = V_G - V_T$

Kinetic Energy	$E_{KE} = \frac{1}{2}mv^2 = \frac{p^2}{2m}$
Relationship between frequency and wavelength of light	$\nu = \frac{c}{\lambda}$
Lorentz Force	$F = q\left(v \times B\right)$
Hall coefficient	$R_H = \frac{\mathcal{E}_H}{JB} = \frac{\mu}{\sigma} = \frac{1}{ne} = \frac{1}{pq}$

hydrogen 1 **H** 1.0079																		helium 2 **He** 4.0026
lithium 3 **Li** 6.941	beryllium 4 **Be** 9.0122												boron 5 **B** 10.811	carbon 6 **C** 12.011	nitrogen 7 **N** 14.007	oxygen 8 **O** 15.999	fluorine 9 **F** 18.998	neon 10 **Ne** 20.180
sodium 11 **Na** 22.990	magnesium 12 **Mg** 24.305												aluminium 13 **Al** 26.982	silicon 14 **Si** 28.086	phosphorus 15 **P** 30.974	sulfur 16 **S** 32.065	chlorine 17 **Cl** 35.453	argon 18 **Ar** 39.948
potassium 19 **K** 39.098	calcium 20 **Ca** 40.078		scandium 21 **Sc** 44.956	titanium 22 **Ti** 47.867	vanadium 23 **V** 50.942	chromium 24 **Cr** 51.996	manganese 25 **Mn** 54.938	iron 26 **Fe** 55.845	cobalt 27 **Co** 58.933	nickel 28 **Ni** 58.693	copper 29 **Cu** 63.546	zinc 30 **Zn** 65.39	gallium 31 **Ga** 69.723	germanium 32 **Ge** 72.61	arsenic 33 **As** 74.922	selenium 34 **Se** 78.96	bromine 35 **Br** 79.904	krypton 36 **Kr** 83.80
rubidium 37 **Rb** 85.468	strontium 38 **Sr** 87.62		yttrium 39 **Y** 88.906	zirconium 40 **Zr** 91.224	niobium 41 **Nb** 92.906	molybdenum 42 **Mo** 95.94	technetium 43 **Tc** [98]	ruthenium 44 **Ru** 101.07	rhodium 45 **Rh** 102.91	palladium 46 **Pd** 106.42	silver 47 **Ag** 107.87	cadmium 48 **Cd** 112.41	indium 49 **In** 114.82	tin 50 **Sn** 118.71	antimony 51 **Sb** 121.76	tellurium 52 **Te** 127.60	iodine 53 **I** 126.90	xenon 54 **Xe** 131.29
caesium 55 **Cs** 132.91	barium 56 **Ba** 137.33	57-70 *	lutetium 71 **Lu** 174.97	hafnium 72 **Hf** 178.49	tantalum 73 **Ta** 180.95	tungsten 74 **W** 183.84	rhenium 75 **Re** 186.21	osmium 76 **Os** 190.23	iridium 77 **Ir** 192.22	platinum 78 **Pt** 195.08	gold 79 **Au** 196.97	mercury 80 **Hg** 200.59	thallium 81 **Tl** 204.38	lead 82 **Pb** 207.2	bismuth 83 **Bi** 208.98	polonium 84 **Po** [209]	astatine 85 **At** [210]	radon 86 **Rn** [222]
francium 87 **Fr** [223]	radium 88 **Ra** [226]	89-102 * *	lawrencium 103 **Lr** [262]	rutherfordium 104 **Rf** [261]	dubnium 105 **Db** [262]	seaborgium 106 **Sg** [266]	bohrium 107 **Bh** [264]	hassium 108 **Hs** [269]	meitnerium 109 **Mt** [268]	ununnilium 110 **Uun** [271]	unununium 111 **Uuu** [272]	ununbium 112 **Uub** [277]		ununquadium 114 **Uuq** [289]				

* Lanthanide series	lanthanum 57 **La** 138.91	cerium 58 **Ce** 140.12	praseodymium 59 **Pr** 140.91	neodymium 60 **Nd** 144.24	promethium 61 **Pm** [145]	samarium 62 **Sm** 150.36	europium 63 **Eu** 151.96	gadolinium 64 **Gd** 157.25	terbium 65 **Tb** 158.93	dysprosium 66 **Dy** 162.50	holmium 67 **Ho** 164.93	erbium 68 **Er** 167.26	thulium 69 **Tm** 168.93	ytterbium 70 **Yb** 173.04
* * Actinide series	actinium 89 **Ac** [227]	thorium 90 **Th** 232.04	protactinium 91 **Pa** 231.04	uranium 92 **U** 238.03	neptunium 93 **Np** [237]	plutonium 94 **Pu** [244]	americium 95 **Am** [243]	curium 96 **Cm** [247]	berkelium 97 **Bk** [247]	californium 98 **Cf** [251]	einsteinium 99 **Es** [252]	fermium 100 **Fm** [257]	mendelevium 101 **Md** [258]	nobelium 102 **No** [259]


GaAs
Si
Ge
BV (v)
C_B (cm^{-3})
10³
10²
10
1
10¹⁴
10¹⁵
10¹⁶
10¹⁷
10¹⁸
10¹⁹

Identities and Formulas

Tangent and Cotangent Identities

$$\tan\theta = \frac{\sin\theta}{\cos\theta} \qquad \cot\theta = \frac{\cos\theta}{\sin\theta}$$

Reciprocal Identities

$$\sin\theta = \frac{1}{\csc\theta} \qquad \csc\theta = \frac{1}{\sin\theta}$$
$$\cos\theta = \frac{1}{\sec\theta} \qquad \sec\theta = \frac{1}{\cos\theta}$$
$$\tan\theta = \frac{1}{\cot\theta} \qquad \cot\theta = \frac{1}{\tan\theta}$$

Pythagorean Identities

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

Even and Odd Formulas

$$\sin(-\theta) = -\sin\theta \qquad \csc(-\theta) = -\csc\theta$$
$$\cos(-\theta) = \cos\theta \qquad \sec(-\theta) = \sec\theta$$
$$\tan(-\theta) = -\tan\theta \qquad \cot(-\theta) = -\cot\theta$$

Periodic Formulas

If n is an integer

$$\sin(\theta + 2\pi n) = \sin\theta \qquad \csc(\theta + 2\pi n) = \csc\theta$$
$$\cos(\theta + 2\pi n) = \cos\theta \qquad \sec(\theta + 2\pi n) = \sec\theta$$
$$\tan(\theta + \pi n) = \tan\theta \qquad \cot(\theta + \pi n) = \cot\theta$$

Double Angle Formulas

$$\sin(2\theta) = 2\sin\theta\cos\theta$$

$$\cos(2\theta) = \cos^2\theta - \sin^2\theta = 2\cos^2\theta - 1 = 1 - 2\sin^2\theta$$

$$\tan(2\theta) = \frac{2\tan\theta}{1 - \tan^2\theta}$$

Degrees to Radians Formulas

If x is an angle in degrees and t is an angle in radians then:

$$\frac{\pi}{180^\circ} = \frac{t}{x} \quad \Rightarrow \quad t = \frac{\pi x}{180^\circ} \ \textbf{and} \ x = \frac{180^\circ t}{\pi}$$

Half Angle Formulas

$$\sin\theta = \pm\sqrt{\frac{1-\cos(2\theta)}{2}}$$
$$\cos\theta = \pm\sqrt{\frac{1+\cos(2\theta)}{2}}$$
$$\tan\theta = \pm\sqrt{\frac{1-\cos(2\theta)}{1+\cos(2\theta)}}$$

Sum and Difference Formulas

$$\sin(\alpha \pm \beta) = \sin\alpha\cos\beta \pm \cos\alpha\sin\beta$$
$$\cos(\alpha \pm \beta) = \cos\alpha\cos\beta \mp \sin\alpha\sin\beta$$
$$\tan(\alpha \pm \beta) = \frac{\tan\alpha \pm \tan\beta}{1 \mp \tan\alpha\tan\beta}$$

Product to Sum Formulas

$$\sin\alpha\sin\beta = \frac{1}{2}[\cos(\alpha-\beta) - \cos(\alpha+\beta)]$$
$$\cos\alpha\cos\beta = \frac{1}{2}[\cos(\alpha-\beta) + \cos(\alpha+\beta)]$$
$$\sin\alpha\cos\beta = \frac{1}{2}[\sin(\alpha+\beta) + \sin(\alpha-\beta)]$$
$$\cos\alpha\sin\beta = \frac{1}{2}[\sin(\alpha+\beta) - \sin(\alpha-\beta)]$$

Sum to Product Formulas

$$\sin\alpha + \sin\beta = 2\sin\left(\frac{\alpha+\beta}{2}\right)\cos\left(\frac{\alpha-\beta}{2}\right)$$
$$\sin\alpha - \sin\beta = 2\cos\left(\frac{\alpha+\beta}{2}\right)\sin\left(\frac{\alpha-\beta}{2}\right)$$
$$\cos\alpha + \cos\beta = 2\cos\left(\frac{\alpha+\beta}{2}\right)\cos\left(\frac{\alpha-\beta}{2}\right)$$
$$\cos\alpha - \cos\beta = -2\sin\left(\frac{\alpha+\beta}{2}\right)\sin\left(\frac{\alpha-\beta}{2}\right)$$

Cofunction Formulas

$$\sin\left(\frac{\pi}{2} - \theta\right) = \cos\theta \qquad \cos\left(\frac{\pi}{2} - \theta\right) = \sin\theta$$
$$\csc\left(\frac{\pi}{2} - \theta\right) = \sec\theta \qquad \sec\left(\frac{\pi}{2} - \theta\right) = \csc\theta$$
$$\tan\left(\frac{\pi}{2} - \theta\right) = \cot\theta \qquad \cot\left(\frac{\pi}{2} - \theta\right) = \tan\theta$$