ECE 3040 Microelectronic Circuits

Exam 1

February 15, 2019

Dr. W. Alan Doolittle 20 minutes

Print your name clearly and largely: Solutions

Instructions:

DO NOT REMOVE ANY SHEETS FROM THIS EXAM! Read all the problems carefully and thoroughly before you begin working. You are allowed to use 1 sheet of notes ~~(1 page front and back) as well as a calculator.~~ There are 100 total points. Observe the point value of each problem and allocate your time accordingly. SHOW ALL WORK AND CIRCLE YOUR FINAL ANSWER WITH THE PROPER UNITS INDICATED. ***Write legibly. If I cannot read it, it will be considered a wrong answer.*** Do all work on the paper provided. Turn in all scratch paper, even if it did not lead to an answer. ***Turn in your notes sheet placed under your exam.*** Report any and all ethics violations to the instructor. A periodic table is supplied on the last page. Good luck!

Sign your name on **ONE** of the two following cases:

I DID NOT observe any ethical violations during this exam:

I observed an ethical violation during this exam:

First 30% **Multiple Choice and True/False**
(Circle the letter of the most correct *answer or answers*)

1.) (3-points) True or [✓ False] The energy bandgap can be considered the energy required to rip an electron out of the material into the vacuum where it conducts electricity.

2.) (3-points) [✓ True] or False: The mobility is the low electric field slope of the drift velocity, in the region where the drift velocity is linearly proportional to the electric field.

3.) (3-points) [✓ True] or False: The product of [the density of states] and [1 -Fermi-distribution function] gives the hole concentration as a function of energy in the valence band.

4.) (3-points) True or [✓ False] If both electrons and holes are exposed to a built in field, as in a solar cell, the charges both move to the same side of the device accumulating on the anode (p-side).

5.) (3-points) True or [✓ False] For a device with a high concentration of defect states or impurity states, the minority carrier lifetime will be very high.

6.) (3-points) [✓ True] or False: In a degenerately doped semiconductor, more than one hole can occupy a given state.

7.) (3-points) [✓ True] or False: Larger bond strength results in higher energy bandgaps.

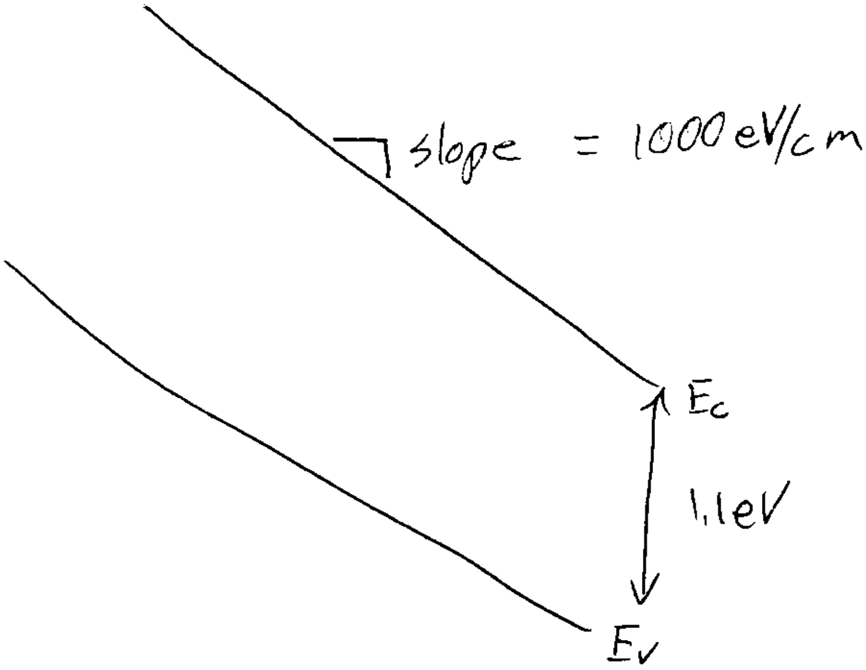
8.) (3-points) [✓ True] or False: The Fermi-Dirac integral of order ½ , the Fermi distribution function and the Boltzmann distribution function are all ways of describing the probability that a state is filled with an electron.

9.) (3-points) True or [✓ False] Auger recombination is only important at low current density or at low optical injection (low optical power).

10.) (3-points) [✓ True] or False: Impact ionization can increase a small current into a large current but is generally noisy current as the multiplication of charge is random and thus, stochastic.

Short Answer ("Plug and Chug"):

11.)(4-points) Sketch and label the energy band diagram of Silicon (1.1 eV bandgap) subjected to an electric field of 1000V/cm showing the conduction and valance bands and labeling the diagram with some indication of how one could derive the material is exposed to this particular electric field. Points deducted for lack of neatness, clarity and missing energy labels and numeric values.



For the following problems (11-12) use the following material parameters and <u>assuming total ionization</u>:

For InP:
n_i=1.3e7 cm^{-3} N_D=1.8e13 cm^{-3} donors N_A=1.6e17 cm^{-3} acceptors
m_p^*=0.6m_o m_n^*=0.08m_o
E_G=1.344 eV Electron mobility, μ_n = 900 cm^2/Vsec Hole mobility , μ_p = 120 cm^2/V-sec
Temperature=27 degrees C

12.)(5-points) Where is the fermi energy (relative to the valence band which is referenced to zero energy)?

$$p_o = \frac{N_A - N_D}{2} + \sqrt{\frac{(N_a - N_D)^2}{4} + n_i^2} = 1.6e17\ \text{cm}^{-3}$$

$$n_o = \frac{n_i^2}{p_o} = 1.06e-3$$

$$E_i = \frac{E_g}{2} + \frac{3}{4}kT\ln\left(\frac{m_p^*}{m_n^*}\right) = 0.711\ eV$$

Several Approaches

1) $p_o = n_i e^{(E_i - E_f)/kT}$

$\boxed{E_f = \text{[redacted]}\ eV}$ 0.109

2) $n_o = n_i e^{(E_f - E_i)/kT}$

$\boxed{E_f = \text{[redacted]}\ eV}$ 0.109

3) $N_c = 2.51\times10^{19}\left(\frac{m_n^*}{m_o}\right)^{3/2} = 5.68e17\ \text{cm}^{-3}$

$n_o = N_c e^{(E_f - E_c)/kT} = 1.06e-3$

$\boxed{E_f = \text{[redacted]}\ eV}$ 0.108

4) $N_v = 2.51\times10^{19}\left(\frac{m_p^*}{m_o}\right)^{3/2} = 1.16e19\ \text{cm}^{-3}$

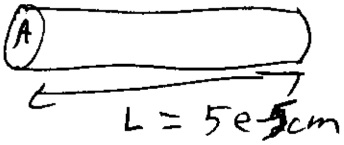
$p_o = N_v e^{(E_v - E_f)/kT} = 1.6e17\ \text{cm}^{-3}$

$\boxed{E_f = \text{[redacted]}\ eV}$

0.109

13.) (8-points) A 25 nm (1 nm = 1e-9 m) ***<u>diameter</u>*** x 500 nm long cylindrical semiconductor resistor is made from the semiconductor from problem 12 is biased on two opposing sides (longest dimension) with 0.9 volts. Determine <u>both</u> the electron and hole <u>currents</u> flowing in the device.

$$A = \left[\frac{(25e-7\ \text{cm})}{2}\right]^2 \pi = 4.909e-12\ \text{cm}^2$$



$$\rho_p = q\mu_p p_o = 0.326\ \Omega\text{-cm}$$

$$\rho_n = q\mu_n n_o$$

$$\rho_n = 6.57e18\ \Omega\text{-cm}$$

wow!

$$R_p = \frac{\rho_p L}{A} = 3.32\ M\Omega$$

$$R_n = \frac{\rho_n L}{A} = 6.7e25\ \Omega$$

$$\frac{V}{R_p} = \boxed{I_p = 2.7e-7\ A = 0.27\ \mu A}$$

$$\boxed{I_n = \frac{V}{R_n} = 1.34e-26\ A}$$

~ 0

Section 3 (more short answer)

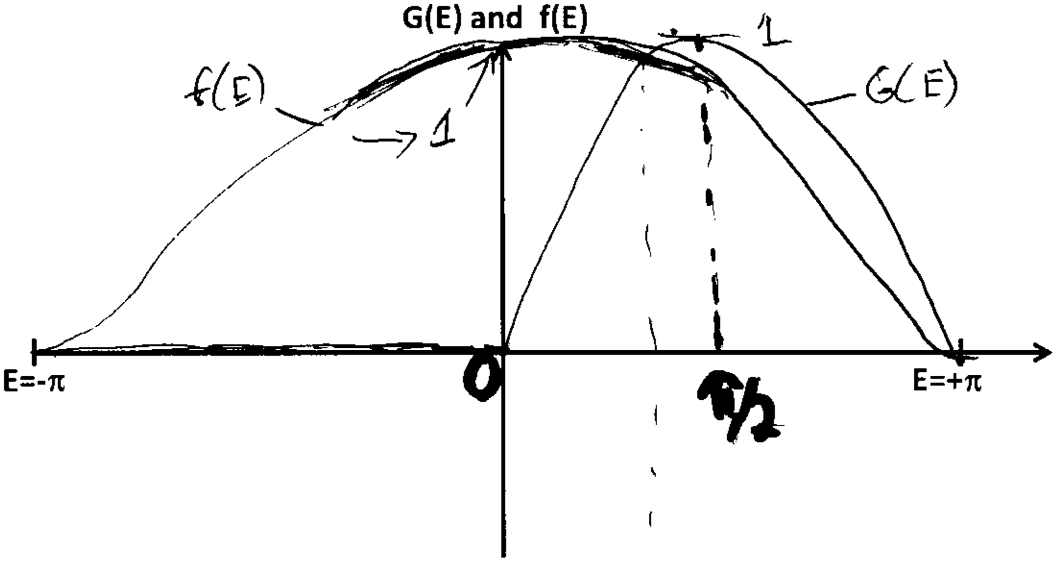
14.) (13-points total) The brilliant and humble Professor Doolittle has found a semiconductor that obeys new "Doolittian Physics". It is found the density of states of this material follows the function:

$$G(E) = \begin{cases} sin(E) \text{ for } 0<E<\pi \\ 0 \text{ elsewhere} \end{cases}$$

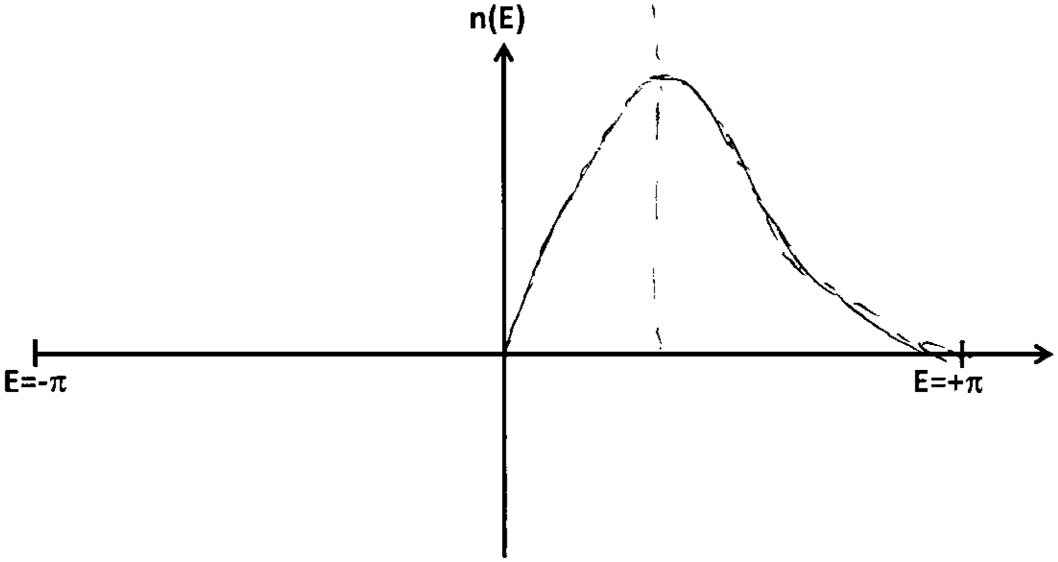
and the fermi distribution function for this new physics is:

$$f(E) = \frac{1}{2}[1 + \cos(E)] \text{ for } -\pi<E<\pi$$

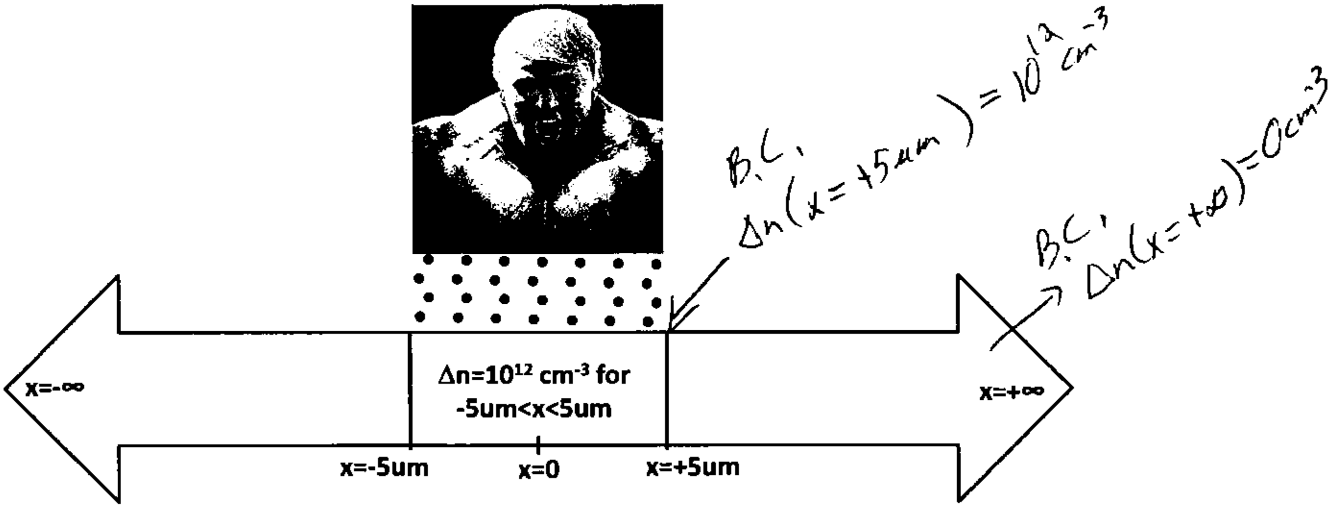
On the same Graph, sketch and label peak magnitudes and peak energies for G(E) and f(E).



Sketch (do not label magnitudes) of the electron concentration versus energy function n(E).



Pulling all the concepts together for a useful purpose:



B.C. $\Delta n(x=+5\mu m)=10^{12}\,cm^{-3}$

B.C. → $\Delta n(x=+\infty)=0\,cm^{-3}$

14.) (40-points) : A semi-infinite slab of GaN semiconductor is to be used as part of new nuclear battery known as a Betavoltaic device. The GaN extends from negative infinity to positive infinity as pictured and is to be considered in 1 dimension (x). The incredible Hulk walks into the room in 1994 and radiates extremely high energy nuclear particles that generate electron hole pairs in a process identical to that as if they originated from light ONLY in the region from -5 to +5 um. All other regions are considered in the dark. The resultant excess electron concentration from + 5 to – 5 um is uniform and equal to 10^{12} cm^{-3}. The semiconductor is doped p-type with an acceptor concentration of 6e15 cm^{-3}, has an intrinsic concentration of 1e-14 cm^{-3} and has a minority carrier lifetime of 5 nanoseconds. If the semiconductor is held at room temperature (27 degrees C), <u>determine the minority carrier diffusion current density</u> at all positions in the semiconductor (+∞ ≥ x ≥ -∞ um). Assume a minority carrier mobility of 1930.5 cm^2/Vsec.

Given: $0 = D_n \frac{d^2\Delta n_p}{dx^2} - \frac{\Delta n_p}{\tau_n}$ General Solution is: $\Delta n_p(x) = Ae^{-x/L_n} + Be^{+x/L_n}$

Given: $0 = D_n \frac{d^2\Delta n_p}{dx^2} - \frac{\Delta n_p}{\tau_n} + G_L$ General Solution is: $\Delta n_p(x) = Ae^{-x/L_n} + Be^{+x/L_n} + G_L\tau_n$

Given: $0 = D_n \frac{d^2\Delta n_p}{dx^2}$ General Solution is: $\Delta n_p(x) = A + Bx$

Given: $0 = D_n \frac{d^2\Delta n_p}{dx^2} + G_L$ General Solution is: $\Delta n_p(x) = Ax^2 + Bx + C$

Given: $0 = D_n \frac{d^2\Delta n_p}{dx^2} + G_{LO}f(x)$ General Solution is: $\Delta n_p(x) = \left[-\frac{G_{LO}}{D_N}\iint f(x)dx^2\right] + Bx + C$

Given: $\frac{d\Delta n_p}{dt} = -\frac{\Delta n_p}{\tau_n}$ General Solution is: $\Delta n_p(t) = \Delta n_p(t=0)e^{-t/\tau_n}$

Given: $0 = -\frac{\Delta n_p}{\tau_n} + G_L$ General Solution is: $\Delta n_p = G_L\tau_n$

$$D_n = \mu_n \frac{kT}{q}$$

$$= 1930.49\,(0.0259) = 50\ \text{cm}^2/\text{sec}$$

$$L_n = \sqrt{D_n \tau} = \sqrt{50 \times 5\text{e-}9} = 5\ \mu\text{m}$$

Extra work can be done here, but clearly indicate which problem you are solving.

$x \geq 5\,\mu m$:

$$\Delta n(x) = A e^{-x/L_n} + B e^{+x/L_n}$$

B.C. $x = +\infty$

$$\Delta n(x=\infty) = A(0) + B\infty$$

$$\Longrightarrow B = 0$$

BC: $x = 5\,\mu m$

$$\Delta n(x = 5\,\mu m) = A e^{-5/5\,\mu m}$$

$$10^{12} = A e^{-1}$$

$$= A\ 0.3678$$

$$A = 2.718\text{e}12\ \text{cm}^{-3}$$

$x \geq 5\,\mu m$: $\Delta n(x) = 2.718\text{e}12\ \text{cm}^{-3}\ e^{-x/5\,\mu m}\ \text{cm}^{-3}$

by symetry $x \leq -5$ $\Delta n(x) = 2.718\text{e}12\ \text{cm}^{-3}\ e^{+x/5\,\mu m}\ \text{cm}^{-3}$

$-5 < x \leq 5$: $\Delta n(x) = 10^{12}\ \text{cm}^{-3}$

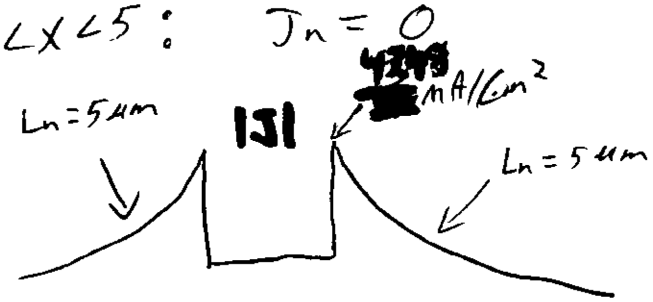
$$J_n = q\, D_n \nabla n$$

$$= -(1.6\text{e-}19)(50\ \text{cm}^2/\text{sec})\left(\frac{2.718\text{e}12}{5\times10^{-4}\ \text{cm}}\, e^{-x/5\,\mu m}\right)$$

$x > 5\,\mu m$: $J_n = \left[\overset{-43.48}{\text{[redacted]}}\ \text{mA}/\text{cm}^2\right]\left[e^{-x/5\,\mu m}\right]$

$x < -5\,\mu m$: $J_n = +\left[\overset{43.48}{\text{[redacted]}}\ \text{mA}/\text{cm}^2\right]\left[e^{+x/5\,\mu m}\right]$

$-5 < x < 5$: $J_n = 0$



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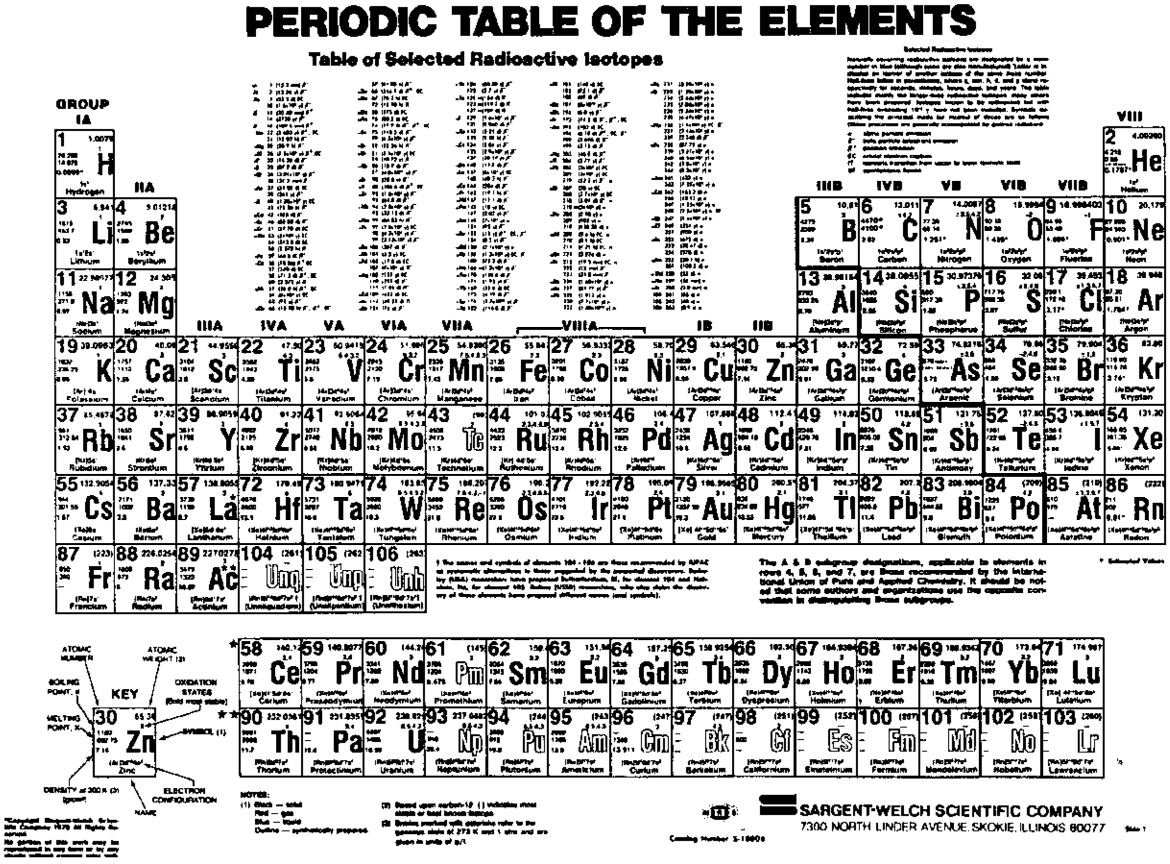

PERIODIC TABLE OF THE ELEMENTS

Table of Selected Radioactive Isotopes

GROUP IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA			IB	IIB	IIIB	IVB	VB	VIB	VIIB	VIII
1 H 1.0079 Hydrogen																	2 He 4.00260 Helium
3 Li 6.941 Lithium	4 Be 9.01218 Beryllium											5 B 10.81 Boron	6 C 12.011 Carbon	7 N 14.0067 Nitrogen	8 O 15.9994 Oxygen	9 F 18.998403 Fluorine	10 Ne 20.179 Neon
11 Na 22.98977 Sodium	12 Mg 24.305 Magnesium											13 Al 26.98154 Aluminum	14 Si 28.0855 Silicon	15 P 30.97376 Phosphorus	16 S 32.06 Sulfur	17 Cl 35.453 Chlorine	18 Ar 39.948 Argon
19 K 39.0983 Potassium	20 Ca 40.08 Calcium	21 Sc 44.9559 Scandium	22 Ti 47.90 Titanium	23 V 50.9415 Vanadium	24 Cr 51.996 Chromium	25 Mn 54.9380 Manganese	26 Fe 55.847 Iron	27 Co 58.9332 Cobalt	28 Ni 58.70 Nickel	29 Cu 63.546 Copper	30 Zn 65.38 Zinc	31 Ga 69.72 Gallium	32 Ge 72.59 Germanium	33 As 74.9216 Arsenic	34 Se 78.96 Selenium	35 Br 79.904 Bromine	36 Kr 83.80 Krypton
37 Rb 85.4678 Rubidium	38 Sr 87.62 Strontium	39 Y 88.9059 Yttrium	40 Zr 91.22 Zirconium	41 Nb 92.9064 Niobium	42 Mo 95.94 Molybdenum	43 Tc (98) Technetium	44 Ru 101.07 Ruthenium	45 Rh 102.9055 Rhodium	46 Pd 106.4 Palladium	47 Ag 107.868 Silver	48 Cd 112.41 Cadmium	49 In 114.82 Indium	50 Sn 118.69 Tin	51 Sb 121.75 Antimony	52 Te 127.60 Tellurium	53 I 126.9045 Iodine	54 Xe 131.30 Xenon
55 Cs 132.9054 Cesium	56 Ba 137.33 Barium	57 La 138.9055 Lanthanum	72 Hf 178.49 Hafnium	73 Ta 180.9479 Tantalum	74 W 183.85 Tungsten	75 Re 186.207 Rhenium	76 Os 190.2 Osmium	77 Ir 192.22 Iridium	78 Pt 195.09 Platinum	79 Au 196.9665 Gold	80 Hg 200.59 Mercury	81 Tl 204.37 Thallium	82 Pb 207.2 Lead	83 Bi 208.9804 Bismuth	84 Po (209) Polonium	85 At (210) Astatine	86 Rn (222) Radon
87 Fr (223) Francium	88 Ra 226.0254 Radium	89 Ac 227.0278 Actinium	104 Unq (261) (Unnilquadium)	105 Unp (262) (Unnilpentium)	106 Unh (263) (Unnilhexium)												

The A & B subgroup designations, applicable to elements in rows 4, 5, 6, and 7, are those recommended by the International Union of Pure and Applied Chemistry. It should be noted that some authors and organizations use the opposite convention in distinguishing these subgroups.

* Estimated Values

*	58 Ce 140.12 Cerium	59 Pr 140.9077 Praseodymium	60 Nd 144.24 Neodymium	61 Pm (145) Promethium	62 Sm 150.4 Samarium	63 Eu 151.96 Europium	64 Gd 157.25 Gadolinium	65 Tb 158.9254 Terbium	66 Dy 162.50 Dysprosium	67 Ho 164.9304 Holmium	68 Er 167.26 Erbium	69 Tm 168.9342 Thulium	70 Yb 173.04 Ytterbium	71 Lu 174.967 Lutetium
**	90 Th 232.0381 Thorium	91 Pa 231.0359 Protactinium	92 U 238.029 Uranium	93 Np 237.0482 Neptunium	94 Pu (244) Plutonium	95 Am (243) Americium	96 Cm (247) Curium	97 Bk (247) Berkelium	98 Cf (251) Californium	99 Es (252) Einsteinium	100 Fm (257) Fermium	101 Md (258) Mendelevium	102 No (259) Nobelium	103 Lr (260) Lawrencium

NOTES:
(1) Black — solid
Red — gas
Blue — liquid
Outline — synthetically prepared
(2) Based upon carbon-12. ( ) indicates most stable or best known isotope.
(3) Entries marked with asterisks refer to the gaseous state at 273 K and 1 atm and are given in units of g/l.

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