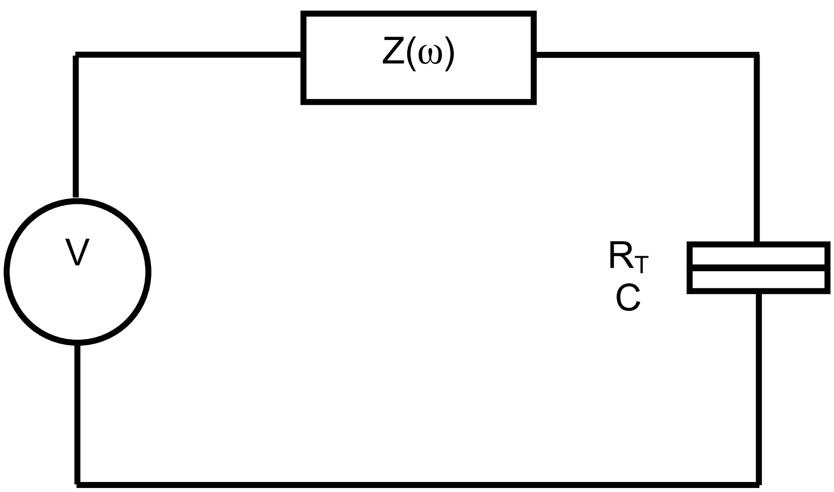
EECS 217C *Nanotechnology*
Midterm
Monday, May 17, 2004

1a	1b	2	3	4	5a	5b	5c	5d	5e	6a	6b	6c	Total
/10	/10	/15	/10	/10	/5	/5	/5	/5	/5	/10	/5	/5	/100

1) A (10 points) What is the smallest dimension that can be lithographically fabricated?

B (10 points) What is the technique that is used to achieve this dimension? (One sentence answer).

2) (15 points) List the requirements for observing Coulomb Blockade behavior in a single tunnel junction.

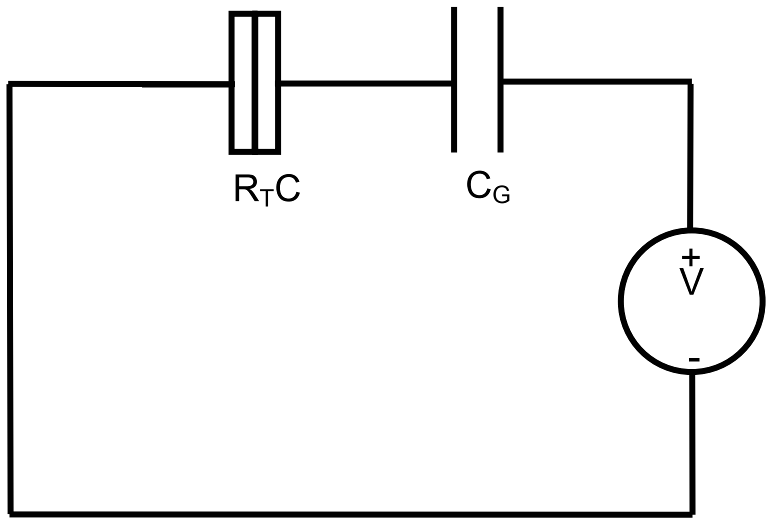


Requirement 1 (5 pts): ________________ $e^2/C >> kT$ ____________________

Requirement 2 (5 pts): _________________ $R_T >> h/e^2$ __________________

Requirement 3 (5 pts): ____________ $Re[Z(\omega)] >> R_T$ for all $\omega < 1/R_K C$ $R_K = h/e^2$ ___

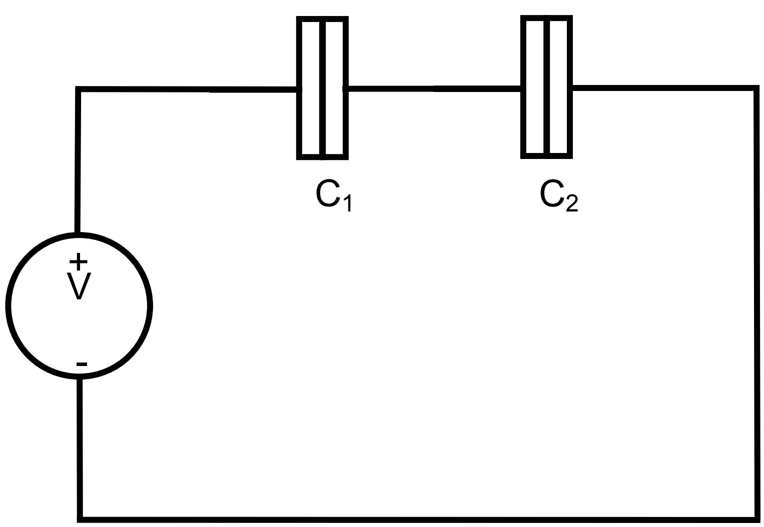
3) (10 points) List the requirements for observing single electron behavior in a single tunnel junction in series with a classical capacitor.



Requirement 1 (5 pts): ___________ $e^2/(C+C_G) >> kT$ ___________________

Requirement 2 (5 pts): ___________________ $R_T >> h/e^2$ _______________

4) (10 points) List the requirements for observing Coulomb blockade behavior for the double tunnel junction system.



Requirement 1 (5 pts): ___________ $e^2/(C_1+C_2) >> kT$ ___________________

Requirement 2 (5 pts): ___________ $R_T >> h/e^2$ _________________________

5) A (5 points) Estimate the spacing between the lowest 2 energy levels for a quantum particle in a box of size 1m x 1m x 1m.

$$E = \frac{\hbar^2}{2m}\left(\left(\frac{\pi}{L_x}\right)^2 n_x^{\ 2} + \left(\frac{\pi}{L_y}\right)^2 n_z^{\ 2} + \left(\frac{\pi}{L_z}\right)^2 n_z^{\ 2}\right)$$

1 1 1 state lowest energy level
1 2 1 or 2 1 1 or 1 1 2 state next highest energy level

$$\Delta E = \frac{3\hbar^2}{2m}\left(\frac{\pi}{L_z}\right)^2 = \frac{3}{2}\frac{\left(1.05x10^{-34}J-s\right)^2}{9.1x10^{-31}kg}\left(\frac{\pi}{1m}\right)^2 = 1.8x10^{-37}J = 1.1x10^{-18}eV$$

B (5 points) Same question, but 1 mm x 1 mm x 1 mm.

$$\Delta E = \frac{3\hbar^2}{2m}\left(\frac{\pi}{L_z}\right)^2 = \frac{3}{2}\frac{\left(1.05x10^{-34}J-s\right)^2}{9.1x10^{-31}kg}\left(\frac{\pi}{1mm}\right)^2 = 1.8x10^{-31}J = 1.1x10^{-12}eV$$

C (5 points) Same question, but 1 μm x 1 μm x 1 μm.

$$\Delta E = \frac{3\hbar^2}{2m}\left(\frac{\pi}{L_z}\right)^2 = \frac{3}{2}\frac{\left(1.05x10^{-34} J-s\right)^2}{9.1x10^{-31} kg}\left(\frac{\pi}{1\mu m}\right)^2 = 1.8x10^{-25} J = 1.1x10^{-6} eV$$

D (5 points) Same question, but 1 nm x 1 nm x 1 nm.

$$\Delta E = \frac{3\hbar^2}{2m}\left(\frac{\pi}{L_z}\right)^2 = \frac{3}{2}\frac{\left(1.05x10^{-34} J-s\right)^2}{9.1x10^{-31} kg}\left(\frac{\pi}{1nm}\right)^2 = 1.8x10^{-19} J = 1.1 eV$$

E (5 points) Of the above "boxes", in which case is the energy level spacing larger than kT at room temperature? For those cases, we call it a "quantum dot", to be studied in detail after the midterm.

Only D, since kT is 1/30 eV at room temperature.

5) One of my goals in this class is to educate you enough to be able to read the nano literature.

The graph below is from Park, et al, "Coulomb blockade and the Kondo effect in single-atom transistors", *Nature,* v. 417, p. 722-725, 13 June, 2002.

It is a plot of the source-drain current as a function of the source-drain voltage for various gate voltages for a molecular scale single electron transistor. For simplicity assume C1 = C2 for this device.
See lecture 8.
The I-V curve is not an "ideal" one as we drew in class, but it is similar, in the sense that is has a "gap" at certain gate voltages, where no current flows. This should give you and idea of the value of C1.

A) (10 points) *Estimate* the numerical value of C1, the tunnel junction capacitance, from this graph.

Referring to slide of lecture 8, the current turns on at a voltage given by:

$$V = \frac{e}{2C_1}$$

From the graph, the turn on voltage is about 0.1 V. So:

$$C_1 = \frac{e}{2V} = \frac{1.6x10^{-19}C}{2(0.1V)} = 8x10^{-19}F$$

B) (5 points) If this were a tunnel junction, with a tunnel barrier of thickness 1 nm, what would the cross-sectional area and the square root of the cross sectional area be, using the simple formula for a parallel plate capacitor?

$$C_1 = \frac{\varepsilon A}{d} \Rightarrow A = \frac{C_1 d}{\varepsilon} = \frac{8x10^{-19}F10^{-9}m}{8.85x10^{-12}(F/m)} = 9x10^{-17}m^2$$

$$\Rightarrow \sqrt{A} = 9.5x10^{-9}m$$

D) (5 points) What is the maximum temperature that you would expect to see single electron transistor behavior for this device?

$$kT \approx \frac{e^2}{2C_1} \Rightarrow T \approx \frac{e^2}{k2C_1} = \frac{(1.6x10^{-19}C)^2}{1.38x10^{-23}J/Kx2x8x10^{-19}F} = 1160K$$