1. **(22 %)** For classical particles following Boltzmann's distribution of energy, please answer the following questions:

   (a) **(4 %)** Please show that the molecular energy distribution is $n(E) = \frac{2\pi N}{(\pi k_B T)^{3/2}}\sqrt{E}e^{-E/k_B T}$ with an energy (E), where k_B is the Boltzmann constant and T is the temperature. Assume the total number of the gas particles is N in a volume of V.

   (b) **(4 %)** Please show that the average energy is $\frac{3}{2}k_B T$. Hint: you might need $\int_0^\infty x^{3/2}e^{-ax}dx = \frac{3}{4a^2}\sqrt{\frac{\pi}{a}}$

   (c) **(14 %)** Express the Boltzmann distribution in terms of speed and show that the most probable speed (v) is $\sqrt{\frac{2k_B T}{m}}$, the root-mean square speed $(\sqrt{\overline{v^2}})$ is $\sqrt{\frac{3k_B T}{m}}$, and the average velocity $(\overline{v})$ is $\sqrt{\frac{8k_B T}{\pi m}}$. Hint: you may need $\int_0^\infty x^3 e^{-ax^2}dx = \frac{1}{2a^2}$ and $\int_0^\infty x^4 e^{-ax^2}dx = \frac{3\sqrt{\pi}}{8a^{5/2}}$

2. **(30 %)** Consider a finite quantum well in Fig. 1 with the potential energy of $V(x) = \begin{cases} 0 & |x| < a/2 \\ V_0 & |x| > a/2 \end{cases}$, where $V_0 > 0$.

   Please answer the following questions:

   (a) **(8 %)** Explain why a wavefunction and its first derivate need to be continuous and finite.

   (b) **(8 %)** Now we have the wavefunctions in this quantum well system as follows:

   $\psi(x) = Ae^{kx} + Be^{-kx}$ if $x > a/2$ and $\psi(x) = Ce^{kx} + De^{-kx}$ if $x < -a/2$, where $k = \sqrt{\frac{2m}{\hbar^2}[V_0 - E]}$ $(0 < E < V_0)$.

   $\psi(x) = F\sin(lx) + G\cos(lx)$ if $-a/2 < x < a/2$, where $l = \sqrt{\frac{2mE}{\hbar^2}}$ $(0 < E < V_0)$.

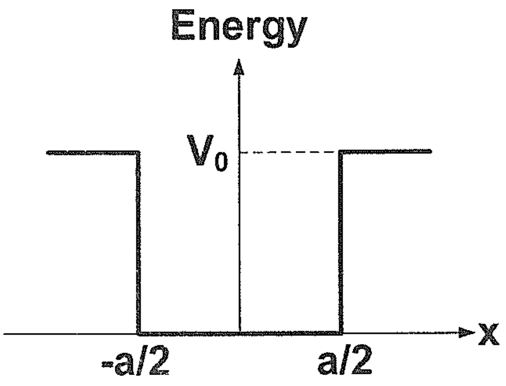

Fig. 1

Please show that

$$(B - C)e^{-\frac{ka}{2}} = 2F\sin\left(\frac{la}{2}\right) \qquad (1)$$

$$(B + C)e^{-\frac{ka}{2}} = 2G\cos\left(\frac{la}{2}\right) \qquad (2)$$

$$k(B - C)e^{-\frac{ka}{2}} = 2Fl\cos\left(\frac{la}{2}\right) \qquad (3)$$

$$k(B + C)e^{-ka/2} = 2Gl\sin\left(\frac{la}{2}\right) \qquad (4)$$

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(c) **(14 %)** By dividing Eq. (1) by Eq. (3) and dividing Eq. (2) by Eq. (4), please show that

$$\frac{1}{-k} = \frac{1}{l} tan\left(\frac{la}{2}\right)$$

$$\frac{1}{k} = \frac{1}{l} cot\left(\frac{la}{2}\right)$$

$$tan\left(\frac{x}{2}\right) = \sqrt{\frac{x_0^2 - x^2}{x^2}} = \sqrt{\frac{x_0^2}{x^2} - 1}$$

$$cot\left(\frac{x}{2}\right) = -\sqrt{\frac{x_0^2 - x^2}{x^2}} = -\sqrt{\frac{x_0^2}{x^2} - 1},$$

where $x \equiv la,\ x_0 \equiv \sqrt{\frac{2m}{\hbar^2} V_0} a.$

Then plot $tan\left(\frac{x}{2}\right)$, $\sqrt{\frac{x_0^2}{x^2} - 1}$ $cot\left(\frac{x}{2}\right)$, and $-\sqrt{\frac{x_0^2}{x^2} - 1}$ vs. x. Also show that there always exists at least one quantum subband in this finite quantum well.

3. **(10 %)** Group-V atoms (e.g. P, As, or Sb) have been doped in Si with an activation energy $E_D = 100$ meV below the conduction band energy level E_C. The Fermi level (E_F) is measured at an energy of 0.15 eV below E_C at room temperature. Assuming $N_C = 2.8 \times 10^{19}$ cm^{-3}, $N_V = 1 \times 10^{19}$ cm^{-3}, $n_i = 1.5 \times 10^{10}$ cm^{-3}, degeneracy of the ionized impurity is two, please calculate
   (a) **(6 %)** concentration of ionized donors N_D^+
   (b) **(4 %)** density of the implanted dopants N_D

4. **(18 %)** A metal-semiconductor contact is formed on Si (electron affinity $\chi = 4.05$ eV) with aluminum (work function $\phi_m = 4.1$ eV). The doping concentration of Si is $N_D = 10^{17}$ cm^{-3}.
   (a) **(6 %)** Please plot the ideal band diagram of the Al-Si M-S junction and mark the Fermi level E_F, the Schottky barrier height Φ_{b0}, and built-in potential barrier Φ_{bi} at equilibrium.
   (b) **(6 %)** If a high density of surface states pin the Fermi level at 0.4 eV above the valence band maximum in this M-S junction interface. Please sketch its band diagram.
   (c) **(6 %)** Please explain the electron flowing direction (e.g. from metal to Si) upon forming the M-S junction with interface conditions provided from both question (a) and (b).

5. **(20 %)** For a conventional planar n-MOSFET, source/drain regions are heavily doped with a concentration of $N_D = 10^{19}$ cm^{-3} and the channel has a doping level of $N_A = 10^{15}$ cm^{-3}. The oxide is 1-nm HfO$_2$ with a dielectric constant of 32 and the gate is aluminum (work function $\phi_m = 4.1$ eV). Trapped charges are inside the oxide and adjacent to the oxide/semiconductor interface with a density of $Q_{SS} = 5 \times 10^{13}$ cm^{-2}. The gate length is 1 μm. The dielectric constant of Si is 11.7. $\varepsilon_0 = 8.854 \times 10^{-14}$ F/cm
   (a) **(5 %)** What is the Flat-Band voltage (V_{FB}) of this MOSFET without considering trapped charge effects (i.e. $Q_{SS} = 0$)?
   (b) **(5 %)** What is the Flat-Band voltage if the trapped charges are considered ($Q_{SS} = 5 \times 10^{13}$ cm^{-2})?
   (c) **(5 %)** What is the threshold voltage (V_{th}) of this n-MOSFET?
   (d) **(5 %)** If Si substrate is biased under 10 V. Please calculate the ΔV_T.

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