1. Quantum mechanics (27%)
   (a) **(4%)** Please write down the time-dependent and time-independent Schrödinger equations in three-dimensions. Assume $\Psi(x,y,z,t) = \psi(x,y,z)\phi(t)$. Note that $\Psi(x,y,z,t) \neq \psi(x,y,z)$. You must write clearly to get full credits.
   (b) **(6%)** For a well-behaved wavefunction, they must be single-valued. In addition, the wavefunction and its first derivative must be continuous. Please explain why from the momentum and energy perspectives.
   (c) **(17%)** Now considering a 1-D potential barrier in Fig. 1. Assume an electron injecting from left ($x < 0$) with a total energy (E) smaller than the barrier potential energy (U_0). What is the tunneling probability in terms of E, U_0, and a?

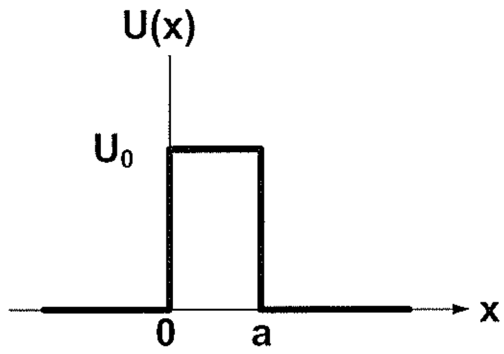

Fig. 1　A barrier potential

2. Particle properties of wave (13%)
   (a) **(6%)** Please explain what "the Ultraviolet Catastrophe" is when the Rayleigh-Jeans prediction is used to represent the energy density of blackbody radiations. Please write the Rayleigh-Jeans and Planck radiation formula and plot the spectra generated by these two formula.
   (b) **(3%)** In Fig. 2-1, for different materials, the frequency of light must be higher than a threshold for photoelectrons to be generated. Please explain why.

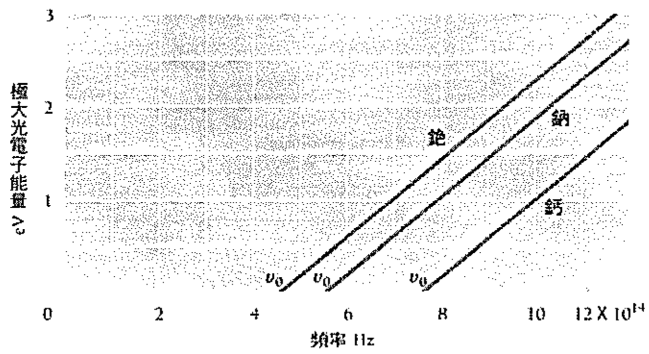

Fig. 2-1　Photoelectron energy vs. frequency for different metals

   (c) **(4%)** See the experimental setup for photoelectric effect in Fig. 2-2. Please explain why for different incident light intensities, the retarding potentials are the same (Fig. 2-3).

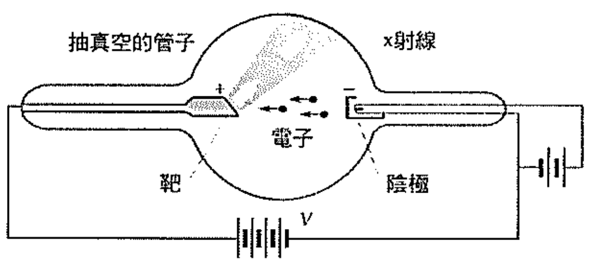

Fig. 2-2　Photoelectric experimental setup

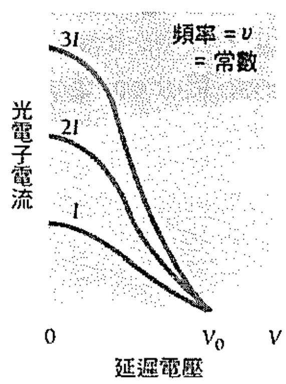

Fig. 2-3　Photocurrent vs. retarding potential

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3. Statistical mechanics (18%)
   (a) **(8%)** Please draw the energy diagrams of a metal and a n-type semiconductor, respectively. You MUST label the vacuum levels, the Fermi levels, the work functions, and the conduction and valence band levels (if needed).
   (b) **(4%)** Assume two energy levels E_1 and E_2 and $E_2 > E_1$. Consider the rate that a particle jumps from E_i level to E_j level as $r_{ij} = k_{ij} f(E_i)[1 - f(E_j)]$, where k_{ij} is a rate constant. Show that in equilibrium, $\frac{k_{12}}{k_{21}} = e^{-\frac{E_2 - E_1}{kT}}$.
   (c) **(6%)** Assume there are two different materials now contacting with each other. Please show that in thermal equilibrium, their Fermi levels are the same. Hint: there are several useful parameters such as density of state (g_1 and g_2), electron numbers (n_1 and n_2), vacancy numbers (v_1 and v_2), and Fermi probability functions (f_1 and f_2). You need to prove $E_{F1} = E_{F2}$ by assuming that the reaction rates of jumping between two materials are the same in equilibrium.

4. Semiconductor devices (42%)
   (a) **(4%)** For a practical pn junction, there is a non-zero current flowing at reverse biases. Please write down the expression of the saturation current density (J_0) given that n_i: intrinsic carrier concentration, D_p and D_n: diffusion constants of holes and electrons; L_p and L_n: diffusion lengths of holes and electrons; N_D and N_A: donor and acceptor concentrations. Assume full carrier activation of dopants at room temperature.
   (b) **(6%)** At low forward biases, if you plot the current (log) vs. voltage (linear) (see Fig. 4-1) and take the derivative of current with respect to voltage, please show that the ideal subthreshold slope SS $\equiv \left[\frac{d \log_{10} I}{dV}\right]^{-1}$ is 60 mV/decade at room temperature.

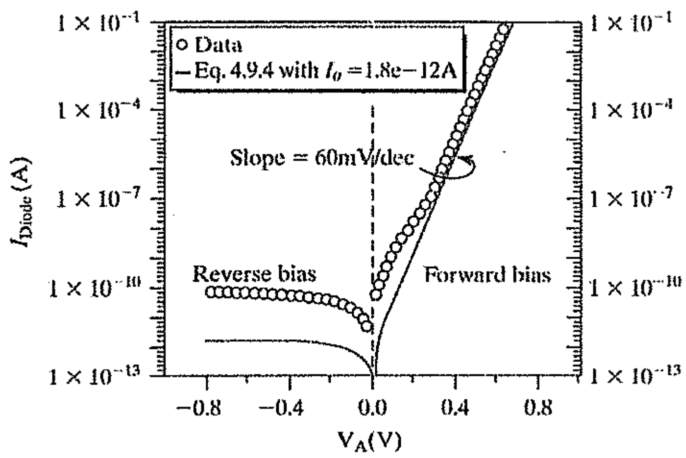

Fig. 4-1 I-V characteristics in a diode with a line and the circles representing the theoretical curve and experimental data, respectively.

   (c) **(6%)** Considering there exists defect centers in the depletion region of a pn junction diode, why is the actual current larger than the ideal current at both reverse biases and small forward biases (see Fig. 4-1)? Explain briefly the mechanisms by drawing the associated band diagrams.
   (d) **(8%)** A MOSFET is the baseline device for logic chips. It actually consists of a capacitor, a resistor, and two diodes. Please label those four components on the cross-sectional MOSFET schematic (Fig. 4-2).

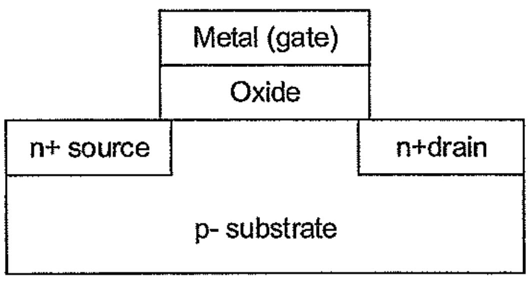

Fig. 4-2 A n-MOSFET cross-section.

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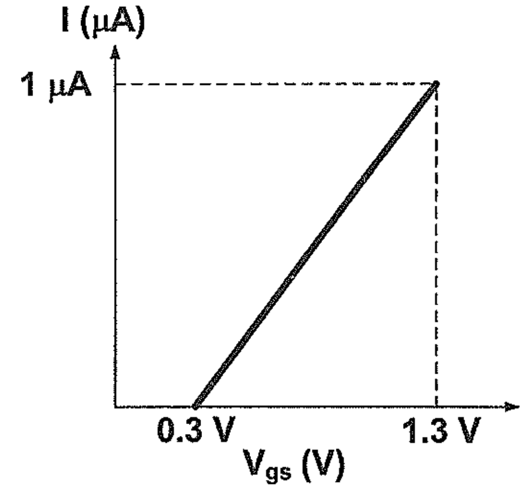

Fig. 4-3　Drain current vs. gate voltage.

(e) **(8%)** Consider a I_d vs. V_{gs} curve with a small V_{ds} = 0.01 V in Fig. 4-3, and assume that the relative dielectric constant (ε_r) of the oxide is 4, W = L, and the oxide thickness is 10 nm. Ignore tunneling leakage through the oxide layer. Please extract the electron mobility in the channel. Note: $\varepsilon_0 = 8.854 \times 10^{-14}$ (F/cm).

(f) **(10%)** If we change the gate length and measure the channel resistance vs. gate length in Fig. 4-4, please extract the mobility. The channel resistance is defined as $R \equiv \frac{V_{ds}}{I}$, where $V_{ds} = 0.01$ V, $V_{gs} - V_{th} = 1$ V, and W = 1 μm. In addition, do you know why with a zero gate length, the resistance is NOT zero? Please explain.

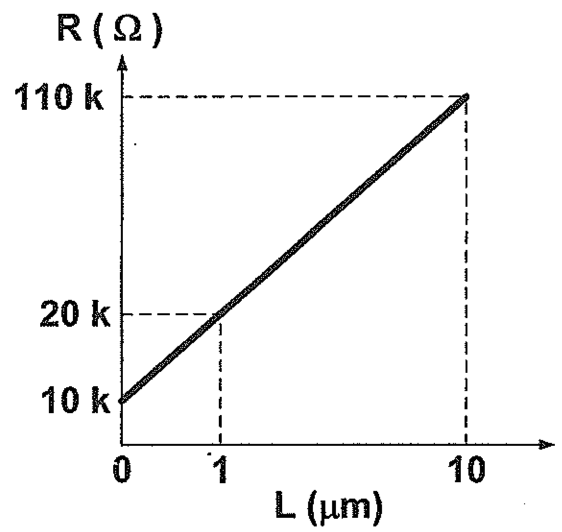

Fig. 4-4　Channel resistance vs. gate length.

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