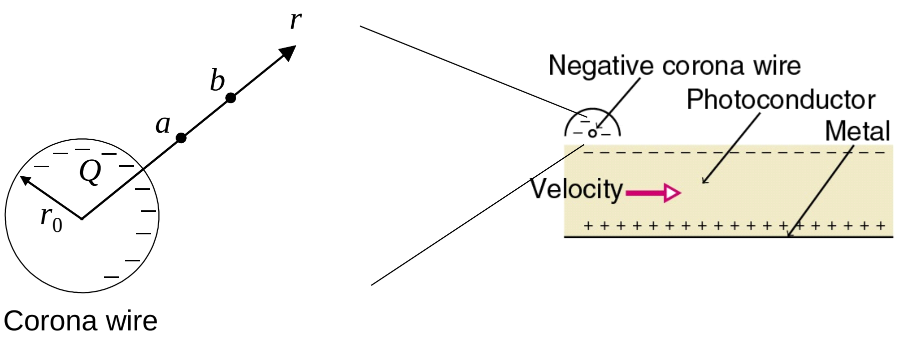
Physics of Modern Technology Exam (NAITEN-10)
8 April 2011, 2 p.m. – 5 p.m.

Start each of the three questions on a new sheet. Write your name and student number on every sheet. Clearly state on sheet 1 the total number of sheets you are handing in.

Question 1

A key element of xerographic printing technology is the corona wire, which charges the photoconductor with static electricity (see the figure below). A corona wire can be considered as a cylindrical conductor of length L, with circular cross section of radius



$r_{0,}$ and holding a charge Q. The electric field for $r > r_0$ is perpendicular to the surface of the wire and can be expressed as

$$E = \frac{1}{2\pi\varepsilon_0}\frac{\lambda}{r},$$

where $\lambda = Q/L$ is the charge density and $\varepsilon_0 = 8.85 \times 10^{-12}$ C^2/Nm^2 the permittivity of free space.

5p a) Determine the electric potential difference, $V_b - V_a$, between the points a and b (with radii r_a and r_b, respectively; see the figure above).

3p b) Assume that $V = \lambda / 2\pi\varepsilon_0$ on the surface of the wire (i.e., for $r = r_0$). Show that the potential at any point with $r > r_0$ can be expressed as

$$V = \frac{\lambda}{2\pi\varepsilon_0}\left(1 + \ln\left(\frac{r_0}{r}\right)\right).$$

2p c) An electron is located on the surface of a wire (i.e., $r = r_0$) of length L = 1 cm, with radius r_0 = 50 μm and charge $Q = -1 \times 10^{-11}$ C. Determine the magnitude and direction of the electrostatic force acting on the electron [e = 1.60×10^{-19} C].

5p d) As a result of this force, the electron accelerates from rest away from the wire. Determine the speed of the electron when it is at a distance of $2r_0$ from the surface of the wire. (In your calculations, use conservation of mechanical energy). The electron has mass $m = 9.1 \times 10^{-31}$ kg.

3p e) If the electric field surrounding the wire becomes very large, free electrons in the air will accelerate to such an extent that the air becomes ionised and hence conductive. Determine the amount of charge Q that the wire has to hold before this can occur. At what charge does it occur if the wire is twice as thick?

2p f) Finally, in no more than 10 sentences, describe the process that enables the corona wire to produce a continuous stream of electrons. This process ensures that the photo conductor is covered by a uniform layer of static electricity.

Question 2

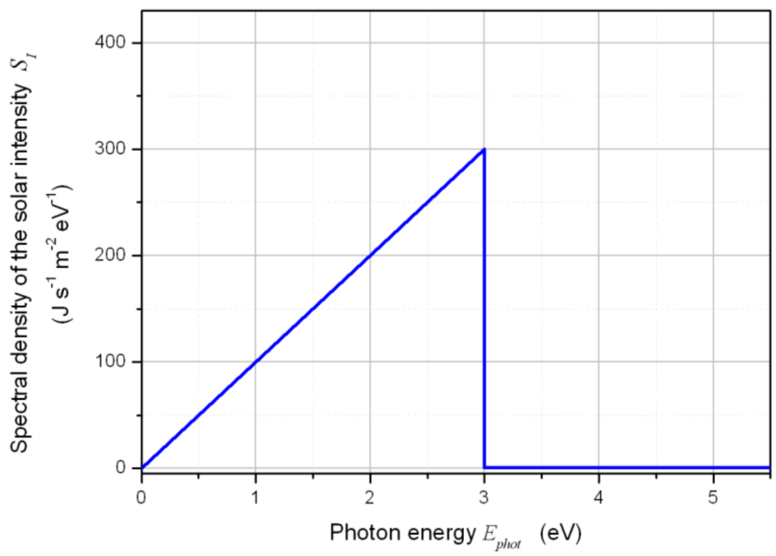
Part 2.1 - Knowledge questions on semiconductors and solar cell materials

2p a) In 10 or so lines, explain the following:
The differences between these three types of semiconductor materials:
1) intrinsic; 2) *p*-type; 3) *n*-type.
One area your explanation must cover is the electrical resistance (i.e. the properties responsible for the resistance of the material in question) and how these materials conduct an electric current.

2p a) In 10 or so lines, explain the following:
Why a solar cell constructed from semiconductor materials has to consist of a *p*-type and an *n*-type layer, one on top of the other (thus forming a *p*-*n* junction).

Part 2.2 - Question on the efficiency of solar cells

Some engineers are working on the development of a new type of solar cell. Their goal is to construct a cell with a longer life by preventing material damage from the ultra-violet (UV) radiation in sunlight. In answering this question, you have to assist their efforts by calculating the maximum possible efficiency of this type of solar cell. The cell in question is made from a single type of semiconductor material with a *p*-*n* junction and a particular value for the *bandgap* (E_{gap}). The engineers have already established that it is essential to apply a UV blocking layer to the top of the semiconductor. This layer blocks all photons with photon energy exceeding the value E_{cut} = 3 eV, but is transparent to photons with less photon energy. You have to find the value of E_{gap} for which the solar cell has the greatest efficiency. You do this by providing answers to the series of sub-questions presented below.



The above figure is a graph of S_I, the spectral density of the intensity of the sunlight, after the light has been filtered by the UV blocking layer. (The actual measurements have been smoothed to produce the graph, so that it is easier to use for the calculations.) For all tests, the intensity of the unfiltered sunlight is 1000 W/m^2.

2p a) Use the graph to calculate the intensity I_{sol} of the sunlight available after filtering through the UV blocking layer. (That is, calculate the amount of solar energy that strikes an area of 1 m^2 each second.)
Hint: you need to perform integration over all spectral components.

1p b) You can assume that every photon absorbed by the semiconductor material is converted into electrical energy (which is not entirely realistic). How many electron-hole pairs are created for each photon? Is there here a dependence on the photon energy *Ephot*?

2p c) To perform this calculation, you need both the spectral density and the number of photons entering the semiconductor material per second and per m^2. Use the notation S_N for this number. The relationship between S_N and S_I is

$$S_N(E_{phot}) = \frac{S_I(E_{phot})}{E_{phot}}.$$

Derive this relationship or explain it in 5 or so lines.

2p d) Use the relationship from sub-question 2.2 c) to calculate the spectrum S_N, and draw a graph of S_N. Hint: start by writing down an analytical expression for the spectrum S_I in the figure above, for the interval $0 < E_{phot} < E_{cut}$ (where E_{cut} = 3 eV). For a constant in this expression, use the notation C.

3p e) Now calculate how much electrical power can be supplied by this type of solar cell with a surface area of A=1 m^2. You can assume that the solar cell supplies an electric current I containing every electron that is excited in the semiconductor material (which is not entirely realistic). The current is supplied at voltage V to an application. You must also assume that all electron-hole pairs that are excited by a photon with $E_{phot} > E_{gap}$ relax very quickly while they are still in the solar cell. Since electrons relax to the bottom of the conduction band and holes relax to the top of the valence band, you can assume that $V = E_{gap}/e$. Although the optimum value of E_{gap} is still unknown, experiments have so far shown that it lies in the interval 0 eV < $E_{gap} < E_{cut}$ (where E_{cut} = 3 eV). Give an expression for the electric power P_{el} as a function of E_{gap} and the other parameters that have already been provided.
Hint: as the unit of S_N is m^{-2} s^{-1} eV^{-1}, you have to integrate over the photon energy E_{phot}, and multiply by the surface area A and the electron charge e to derive the current I from S_N.

3p f) Use the result from 2.2e) to calculate the value of E_{gap} that gives a maximum value for P_{el}.

3p g) What is the value of P_{el} for the result from 2.2 f), and what is the efficiency of the solar cell corresponding to this value?

Question 3

5p a) Under conditions of moderate illumination, the pupil of the human eye is approximately 2 mm in diameter. Consider the eye as a telescope. Calculate (using the Rayleigh criterion) the limit of the eye's angular resolution. What is the maximum distance of a (clear) scale to the eye at which a difference of 1 millimetre can just be distinguished? Is the resolving power of the eye greater at twilight or in the bright sunshine of high noon? Is the eye's depth of field greater at twilight or in the bright sunshine of high noon?

3p b) What type of lens aberration limits the resolution of electron transmission microscopes? Give a well-founded explanation of how this aberration works and thereby how it limits the resolution (by showing ray paths for example).

4p c) A limiting factor for magnetic memories (in hard disks for example) is the superparamagnetic limit. This limit holds for smaller domains when the magnetic material used becomes harder. Soft magnetic materials on the other hand are used specifically in transformers. Show the typical hysteresis loops (plot of the magnetisation of material M against the external magnetic field H) for hard and soft magnetic materials (with the similarities and differences between hard and soft materials made very clear). The harder the magnetic material, the more difficult it becomes to write data, for example, on a hard disk (or to erase data from the medium). What would be a good solution to overcome this problem?

3p d) X-rays (made in hospitals) show contrast in the images by utilising the photoelectric effect, whereas radiation used in the treatment of cancer makes specific use of Compton scattering. Explain the similarities and differences between the photoelectric effect and Compton scattering.

5p e) Proton therapy is potentially much more effective than radiation with photons, which is currently the standard treatment method. At what speed are the protons and photons travelling before they reach the body if the photons have energy of 15 MeV and the protons are accelerated with energy of 150 MeV. Remember that this energy is in addition to the energy m_0c^2 of the protons, where m_0 is their mass at rest and c is the speed of light. The total relative energy of the protons is therefore 150 MeV + m_0c^2; m_0 is 1.67×10^{-27} kg, c is 3.00×10^{8} m/s, the Planck constant h is 4.14×10^{-15} eV s or 6.62×10^{-34} J s, and hence the unit charge e is 1.60×10^{-19} C.