EE 119   Homework 8 Solution

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1. **Solar Cell**

Tired of paying outrageous energy bills and afraid of future rolling blackouts, Uncle Mac is determined to become energy self-sufficient. He wants to power his house with solar panels and comes to you for help. You know that a solar cell can be modeled simply as photodiode where the built-in potential of the p-n junction provides the output voltage and the intensity of the sun converted into electrons provides the output current (see figure 1). He finds in a catalog 10cm x 10cm solar cells made of doped crystalline silicon (Bandgap = 1.1eV, estimated output voltage = 0.5V, quantum efficiency = 15%, loss due to heat generated by photons with energy greater than the bandgap = 40%, cost per panel including all electronics = $20.00). Not sure what to do, he comes to you for help.

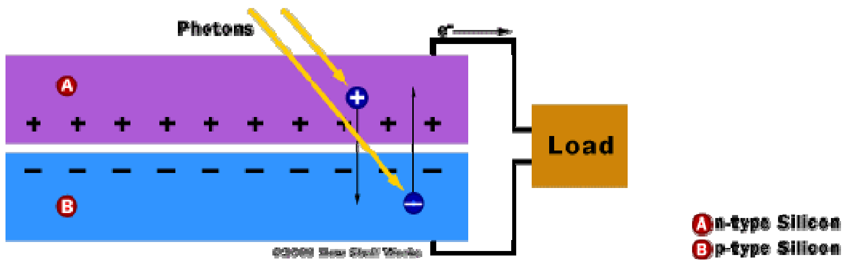


Figure. 1

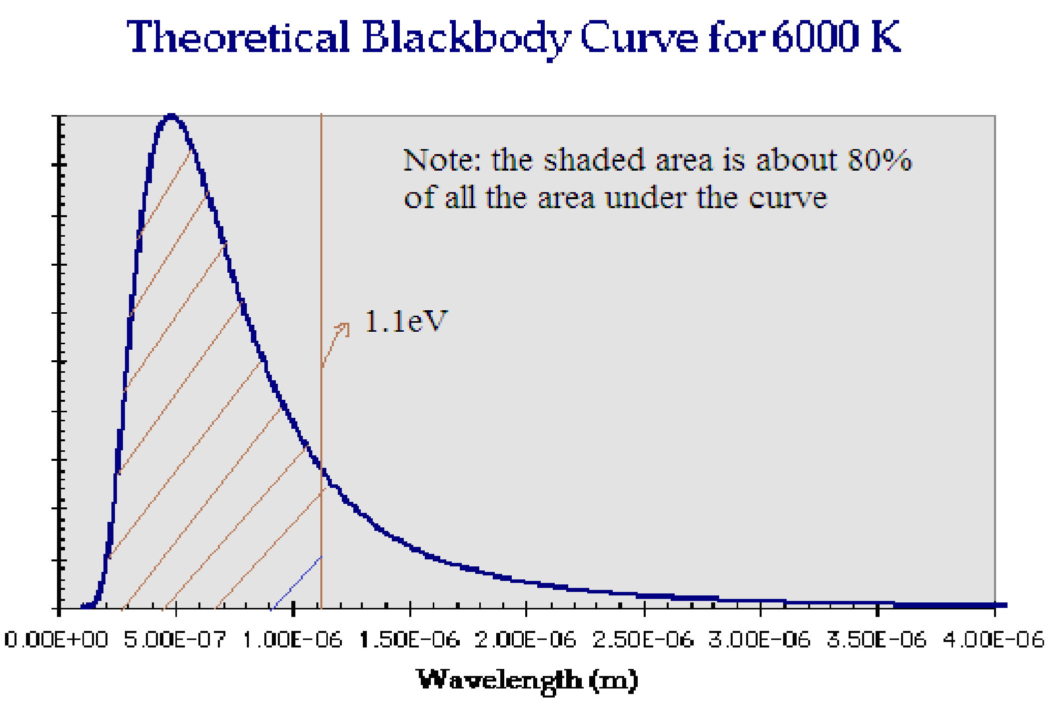


Figure 2

You know that the intensity spectrum of the sun can be modeled as that of 6000K blackbody radiation (see figure 2), normalized to 1000 W/m^2 (average intensity at the earth's surface). Also, knowing that Uncle Mac's house requires on average 550W of power at 120V, help Uncle Mac to design a system of solar cells to power his house. How much is it going to cost? Assume here the absorption of the above-bandgap light in Si is complete.

He also sees in the catalog a solar cell made of GaAs (Bandgap = 1.42eV). Comment on what advantages and disadvantages you might see to use GaAs instead of Si.

Solution:

Of the 1000W/cm2 Sun power incident on the earth's surface, about 80% of the radiation has the photon energy above the 1.1eV required to excite an electron over silicon's bandgap. The quantum efficiency of the solar cell tells us that 15% of that part of radiation is converted to electron-hole pairs and 40% of this is lost to heat.

Therefore the portion of the Sun power that contributes to generate photo-current on each panel is

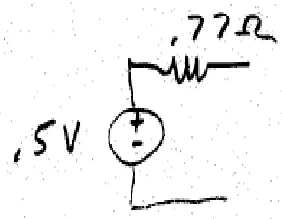
$$P = 1000W/m^2 \times (0.1m \times 0.1m) \times 80\% \times (1-40\%) \times (15\%) = 0.72W/panel$$

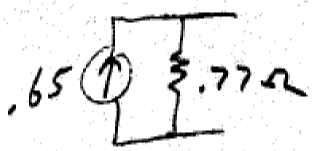
which corresponds to photo-current of

$$I = q\frac{P}{h\nu} = 1.6\times10^{-19} \times \frac{0.72}{1.1\times1.6\times10^{-19}} = 0.65A$$

For each panel, $V_o = 0.5V$, $I = 0.65A$

Since Uncle Mac needs V = 120V, P = 550W, => I = 4.58A,

and for each cell, 

or 

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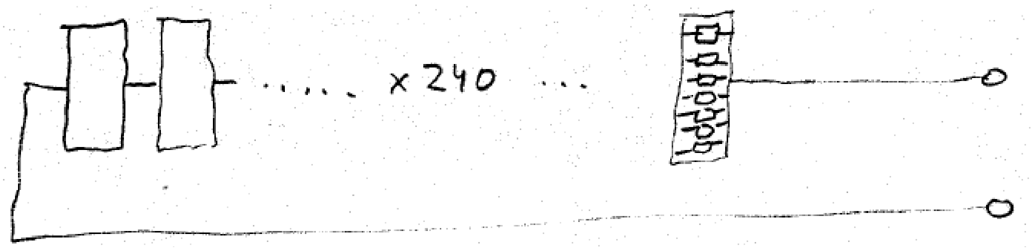
he needs 240 sets of panels in series with 7 panels in each set.



The number of panels he needs is 240 x 7 = 1680.

So the cost is \$20 x 1680 = \$ 33,600. Obviously, this is pretty expensive.

For solar cells made of GaAs, energy bandgap is 1.42eV, corresponding to a cut-off wavelength of 873nm. Thus, less portion of the sun radiation (about 65% instead of 80%) are absorbed by the solar cell. However, being a direct bandgap semiconductor, the absorption process in GaAs is more efficient than that in Si, resulting in a larger fraction of above-bandgap light absorption (see the first figure in Lecture Note 14). Also for GaAs, loss due to heat generated by photons with energy greater than the bandgap is less. All these present some of the design trade-off.

2. **Charge-Coupled Devices**. Calculate the pixel data transfer rate in bytes/sec (1 byte per pixel) for a CCD camera (bytes/sec), operating at a video frame rate of 30 frames/sec, with a) 256 pixels by 256 pixels, b) 242 pixels by 770 pixels, c) 1024 pixels by 1024 pixels, and d) 4192 pixels by 4192 pixels.

   Solution: At a video frame rate of 30 frames/sec, the data transfer rate (bytes/sec) for a CCD camera is

   pixels / frame × frame rate (frames/sec) × 1 byte / pixel

   So for (a) the pixel data transfer rate is

   $256 \times 256 \times 30 = 1966080 = 2\text{MB/s}$

   Similarly, (b) $242 \times 770 \times 30 = 5.59\text{MB/s}$

   (c) $1024 \times 1024 \times 30 = 31.5\text{MB/s}$

   (d) $4192 \times 4192 \times 30 = 0.527\text{GB/s}$.

3. **Well depth**: The potential well in a CCD pixel will continue to collect all available electronic charges until it is filled with electrons. When the potential well is completely filled with charges, this is the saturation point of the detector and this is the maximum capacity of the potential well. In this problem, you will calculate this maximum well capacity, also called the well depth.

   We have a CCD camera with 242 pixels (vertical) by 350 pixels (horizontal), operating at a video frame rate of 30 frames/sec, and each pixel is made with a MOS structure. The size of the CCD is 4.8mm (V) by 6.4mm (H). The CCD is saturated when the incident power density is $0.05\mu W/cm^2$ at the wavelength of 630nm. The quantum efficiency at that wavelength is 56%. You can ignore the gap between each pixel.

   (a) Calculate the well depth of the CCD (in # of electrons).

   Solution: At the wavelength of 630nm, the saturation power for each pixel is

   $$P_{pixel} = I_{sat} \times A_{pixel} = 0.05\mu W / cm^2 \times \frac{0.48cm \times 0.64cm}{242 \times 350} = 1.813 \times 10^{-7}\ \mu W$$

   which corresponds to incident photon flux per pixel of

$$\phi_{pixel} = \frac{P_{pixel}}{h\nu} = \frac{1.813\times10^{-7}\,\mu W}{\frac{1.24}{0.63}\times1.6\times10^{-19}\times10^{6}\,\mu J} = 5.757\times10^{5}\,/\sec$$

With the quantum efficiency of 56%, the number of photo-electrons produced at each pixel well per second is

$$n_e\,/\sec = \phi_{pixel}\cdot QE = 5.757\times10^{5}\,/\sec\times56\% = 3.224\times10^{5}\,/\sec$$

As the video frame rate is 30 frames/s, the photo-electrons captured at each pixel well per frame is then

$$n_{se} = 3.224\times10^{5}\,/\sec\times1/30\sec = 1.075\times10^{4},$$

which corresponds to the maximum well capacity.

(b) Now, we want to use that CCD to detect radiation from a laser with wavelength of 193nm. The quantum efficiency at that wavelength is 3%. What is the saturation power density for this application?

Solution: With the maximum well capacity calculated in (a), the saturation power density for the application in (b) is

$$I_{sat} = \frac{P_{pixel}}{A_{pixel}} = \frac{\frac{n_{se}}{QE}\cdot h\nu\times frame\_rate}{A_{pixel}} = \frac{\frac{1.075\times10^{4}}{3\%}\times\frac{1.24}{0.193}\times1.6\times10^{-19}\times30}{\frac{0.48cm\times0.64cm}{242\times350}}$$

$$= 3.044\mu W/cm^{2}$$

3. **Picture Contrast Ratio (PCR) and gray scale**. The electro-optic characteristics for a TN-LCD and STN-LCD are given in Figure 3. Two vertical lines in each graph indicate the OFF-ON rms operating voltages for 240:1 multiplexing (this is a dual scan VGA display, so M = 240 instead of 480)

(a) Which graph corresponds to the characteristics of TN-LCD? Why?

Solution: Figure 3(a) corresponds to the characteristics of TN-LCD because the luminance-voltage curve is less steep, reflecting the lesser sensitivity of the twisted nematic liquid crystal compared to the super-twisted nematic LCD.

(b) The Pixel Contrast Ratio (PCR) is defined as follows. Calculate the PCR for a VGA TN-LCD display.

$$PCR = \frac{L_{\text{on}}+(M-1)L_{\text{off}}}{ML_{\text{off}}}$$

M = number of display rows, L = Transmitted luminance

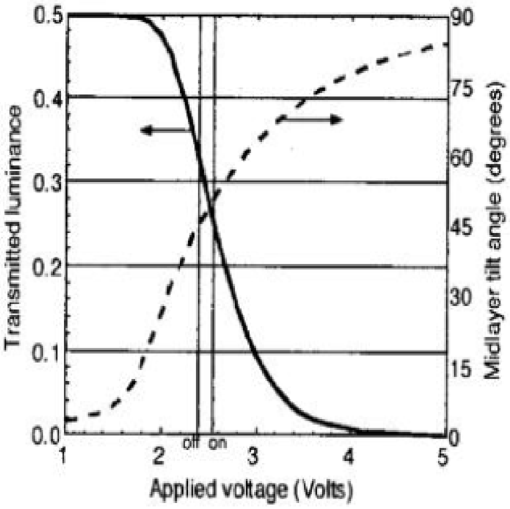


Figure 3 (1)

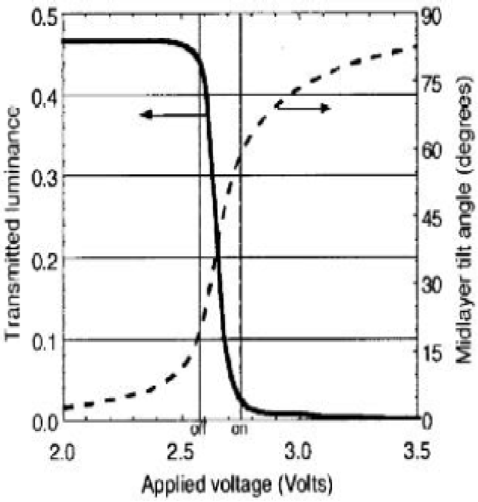


Figure 3(2)

Solution:

For the TN-LCD, $L_{on} = 0.33$ and $L_{off} = 0.25$, so the PCR is

$$PCR = \frac{0.33 + 239 \times 0.25}{240 \times 0.25} = 1.0013$$

(c) Calculate the PCR for a STN-LCD display.

Solution:

For the STN-LCD, $L_{on} = 0.44$ and $L_{off} = 0.02$, so the PCR for a STN-LCD display is

$$PCR = \frac{0.44 + 239 \times 0.02}{240 \times 0.02} = 1.0875$$

The PCR for the STN-LCD is higher because the super-twisted liquid crystal is more sensitive to voltage changes.

(d) What is the maximum allowable change in pixel voltage during a single frame time for a 6 bit gray scale for TN-LCD and STN-LCD? For which display is it easier to control the gray scale?

Solution:

For TN-LCD, the difference in transmitted luminescence between two adjacent levels of gray is 0.5/64 = 0.0078 luminescence/ level.

The maximum slope of this graph is ~0.3 luminescence / 0.8V = 0.375 luminescence/V, so the maximum allowable change in pixel voltage is

(0.0078 luminescence/ level)/(0.375 luminescence/V) = 21mV.

For STN-LCD, the difference in transmitted luminescence between two adjacent levels of gray is 0.47/64 = 0.00734 luminescence/ level.
The maximum slope of the graph is ~0.4 luminescence / 0.4V = 1 luminescence/V, so the maximum allowable change in pixel voltage for STN-LCD is (0.00734 luminescence/ level)/(1 luminescence/V) = 7.3mV.

Comparing the voltage values for the two kinds of LCDs, obviously it is easier to control the gray scale in TN-LCD since its required change in voltage is more relaxed than that for STN-LCD.

5. **Laser operation**

(a) A particular laser has a cavity of two mirrors with $R_1 = .97$ and $R_2 = .9999$. What must the round-trip gain G be for steady-state laser oscillation? Assume there are no losses in the laser except for the loss from mirrors. Remember that for the steady-state laser oscillation, round-trip gain ($G = e^{2gL}$) must equal to round-trip loss.

Solution: For this laser, light gets attenuated per round trip in the cavity by
$R_1 R_2 = 0.9699$
Therefore, the gain for steady-state laser must be
$G = 1/ R_1 R_2 = 1.031$.

(b) The gain medium has a length of 1 micron. For steady-state oscillation, what is the gain coefficient, g, in /cm?

Solution: As $G = e^{2gL} = 1.031$, the gain coefficient g is then

$$g = \frac{\ln G}{2L} = 152.65 / cm$$