Photovoltaic effect: Diode IV-characteristics

By
Stefan Clementz, 860421-0198, scl@kth.se
Karl Jonsson, 871226-0390, karljo@kth.se
Sammy Mannaa, 871216-0491, sammym@kth.se

Instructor
Tobias Övergaard, tobiasov@kth.se

Course
IM2601

Date
2011-04-21

Introduction

A solar cell is a variant of a diode which is designed to convert light to electrical current. In fact, the solar cell is a large variant of a so called p-n junction. The p-n junction is composed of two parts of doped semiconductors, with acceptor atoms on the p-side and donor atoms on the n-side. In a region between the p- and the n-side the electrons of the donor atoms will move to the acceptor atoms. The diffusion of electrons leaves the p-side negatively charged and the n-side positively charged which gives rise to an electric field, a field which will cancel the flow of electrons. In effect there will be a permanent electric field in the region.

When the cell is illuminated by light of sufficient energy so as to overcome the band gap, electrons will be excited and a free electron and a hole is created. These are accelerated in opposite direction by the electric field and a current is generated. Then the voltage that occurs when a p-n junction is illuminated is called the photovoltaic effect

In this lab we will study a solar cell made of a thin film of Silicon (Si). The band gap Eg of Si, i.e. the energy needed to lift an electron to a conduction band, is 1.11 eV at T=300 K (Kittel p.190). Say that a monochromatic light source is to power the cell, the minimum frequency of the light hitting the cell needed to create a voltage is 2.7e+14 Hz, corresponding to the wavelength 1100 nm, which lies in the infrared spectrum. Thus shorter wavelengths of electromagnetic radiation, such as visible light, will be able to drive the cell.

In this report we will give an illustration of some of the details in how a solar cell works. One such detail is the way a diode conducts a current I in response to the applied terminal voltage V.

Experimental procedure

The materials used in the lab are listed below.

- 1 Power Cassy^{TM},
- 1 black power cable,
- 1 RS232 cable,
- 1 solar cell, polycrystalline silicon (Si) thin film, in a plastic box,
- 2 cables with banana plugs,
- 1 large ruler,
- 1 desk lamp and
- 1 computer with Cassy Lab.

In order to obtain an IV curve a triangular voltage of amplitude 0.57 V with frequency 0.2 Hz was fed to the solar cell by the Power Cassy, see Figure 6 for a circuit model of the system. During one cycle the current I through the sample was measured with with time step $200 \mu s$ using the Power Cassy^{TM} interface. The actual set up is shown in Figure 1.
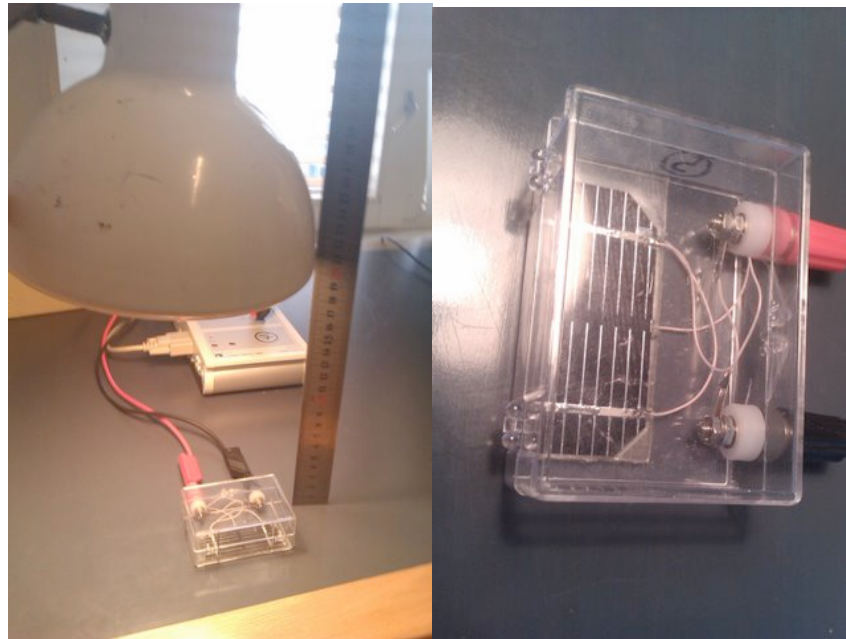
Figure 1. Left: The experimental set up. The solar cell is placed under a desktop lamp at distance r. Collection of data was performed using the Power Cassy connected to a PC with software Cassy Lab. **Right:** A close up of the solar cell.

At first, a measurement was performed with no incoming light. Thereafter the lamp was used to illuminate the solar cell. The distance between the light source and the solar cell was varied in the range 4-54 cm. For each distance, a measurement was performed in the way described above.

Measurement Results

The curve in Figure 2 shows the IV curve for the solar cell when no light (except ambient light) is incident. Each sampled point for I is an average of five points with the same applied voltage, so as to minimize the noise.

In Figure 3 the IV-curves for the solar cell is shown. Each curve corresponds to a different distance between the lamp and the solar cell.

Figure 4 illustrates a PV-plot where each curve corresponds to different lamp to cell distances.
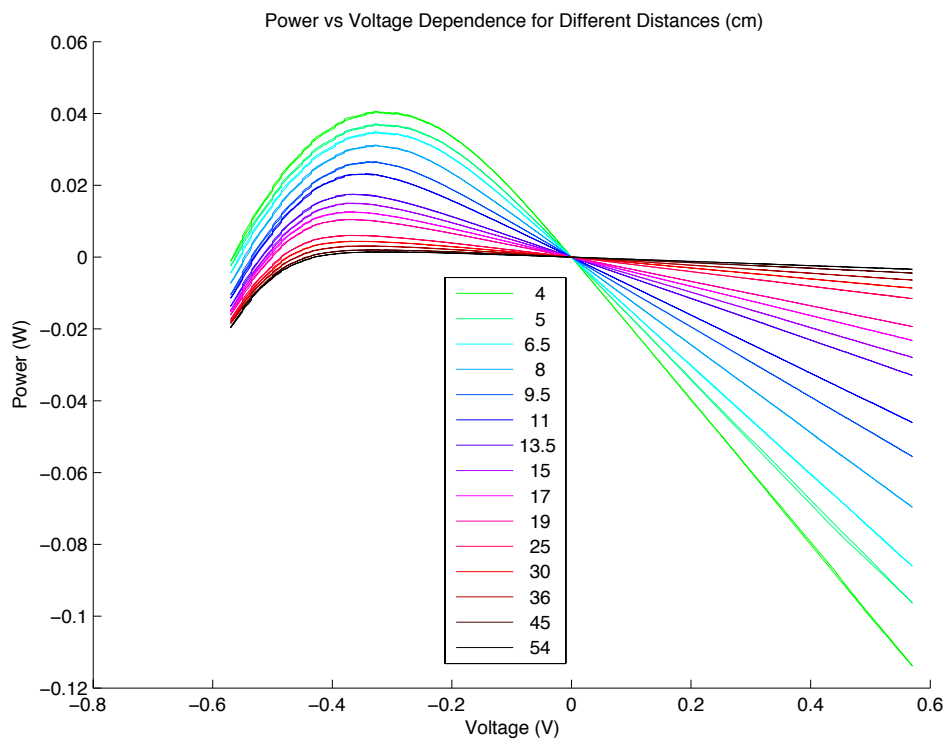
Figure 5 shows the functional relationship between the maximum power of the cell and the distance between lamp and cell.
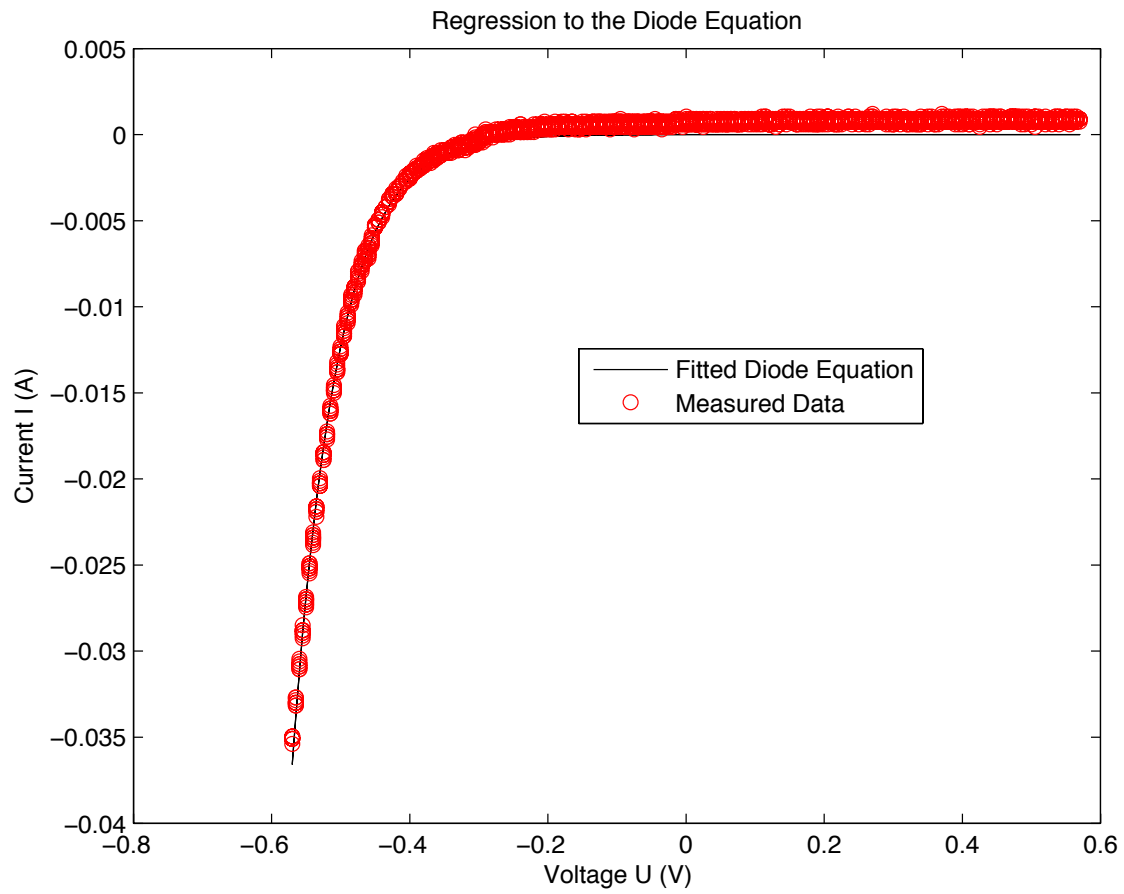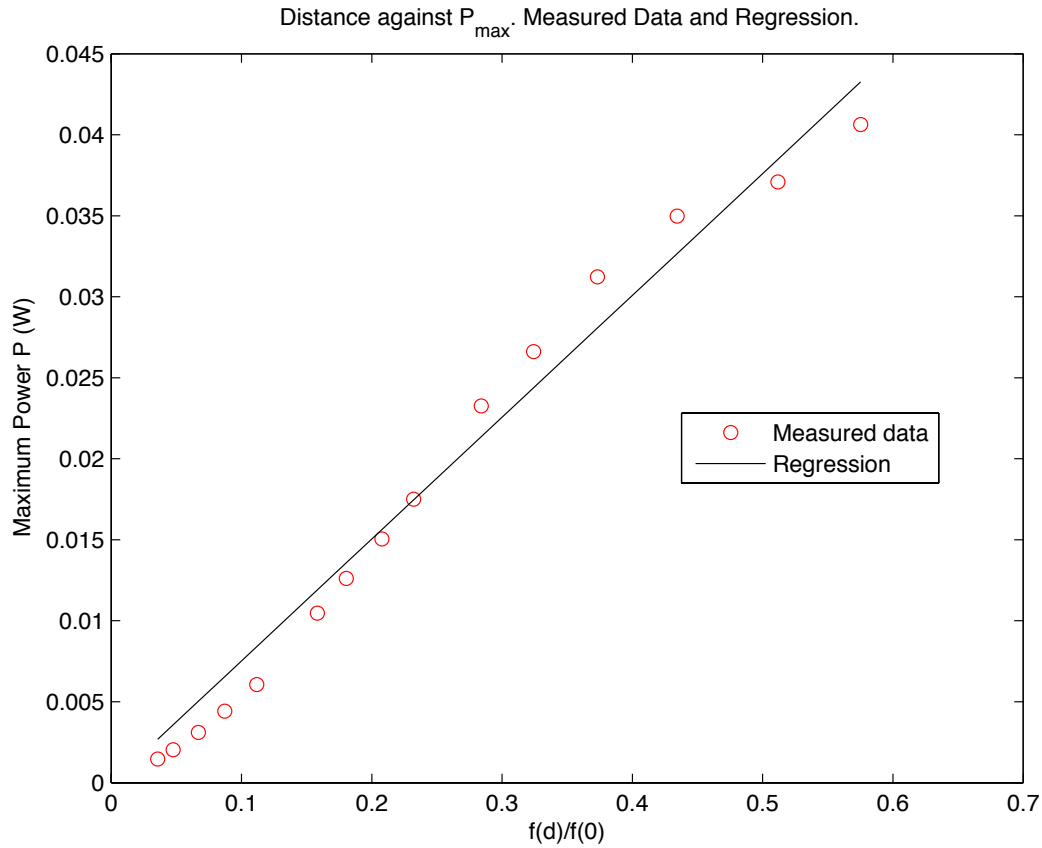
Figure 2. IV curve for the solar cell, no illumination. The curve in black shows a fitted function to observed data.
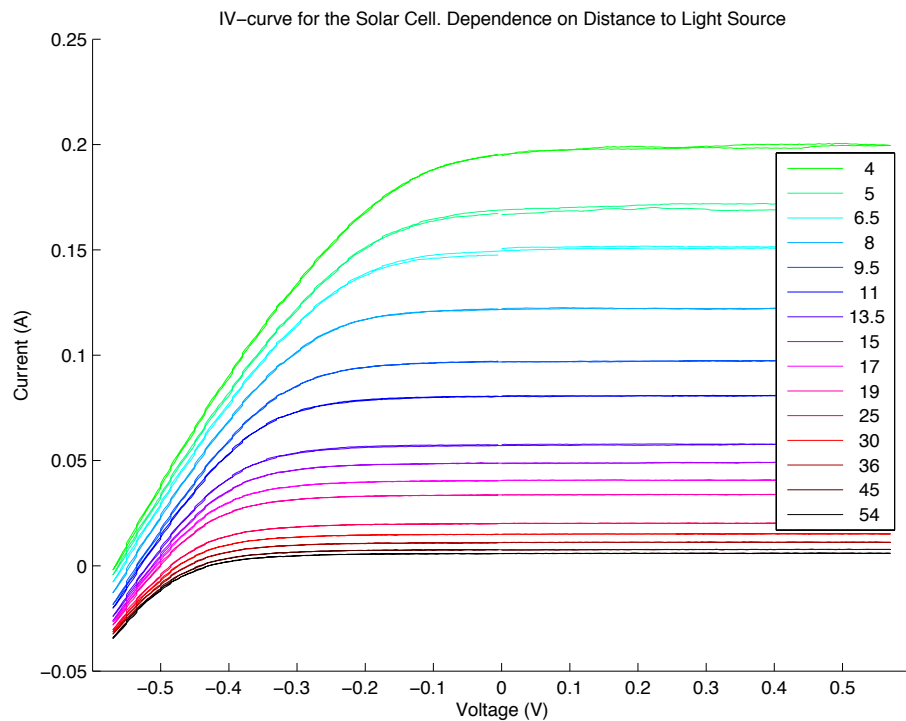
Figure 3. IV curve for the solar cell at different lamp to cell distance.

Figure 4. Power versus voltage for different distances to the light source.

Distance against P_{max}. Measured Data and Regression.

Figure 5. Shows the functional relation between the maximum power and distance between the lamp and the solar cell. The x-axis is transformed to show: $P_{max} = f(d) = \dfrac{k}{(d + x_0)^2}.$

Discussion

Regression to the Diode Equation

From theory we have the following relation between I and V for a diode,

$$I = I_{sat}(1 - e^{-eV/k_B T}) = I_{sat}(1 - e^{-V/V_0})$$

called the *diode equation* where e is the fundamental charge, T being the surrounding temperature and n the ideality factor. After fitting the data to the diode equation with respect to the parameters V_0 and I_{sat} we obtain: $I_{sat} = 5.194e - 4\,A$ and $V_0 = 6.43e - 2\,V$.

The values were obtained using non-linear least squares optimization (see appendix for code). A graphical representation of the regression is shown in Figure 2. We conclude that the

observed data follows the diode equation to great extent. The deviation seen for positive voltage, i.e. the measured data lying above the fitted curve, is due to that the solar cell conducts a small current in the backward bias, which is not accounted for in the diode equation.

The ideality factor is found to be 2.5. For an ideal diode this value should be close to 1. One effect influencing that the diode is not ideal is the due to the fact that recombination of holes and electrons occur. This effect increases as the purity of the sample decreases.

At zero bias, there will still be a current. For the case depicted in Figure 2, no light from the light bulb is present. There will however be ambient light present which will result in the solar cell producing electricity. As more light is illuminating the cell, more current is flowing at zero bias, which is amply shown in Figure 3.

Maxium Power versus Lamp-to-Cell distance
The power delivered to the solar cell from the lamp is proportional to the distance squared, assuming that light is spread equally in all directions over the surface area of a sphere with radius equal to the cell-to-lamp distance. We introduce the parameter x_0 to handle any systematic error in the distance measurement, obtaining:

$$P_{max} = f(d) = \frac{k}{(d + x_0)^2}$$

A correction x_0 is needed as the distance d was measured from table to the edge of the lamp while the appropriate distance should have been measured from the light source to the solar cell. Using built in functionality of MATLAB and non-linear least squares, the constants k and x_0 were found: k=11.86 W and x_0 = 12.56 cm and thus:

$$f(d) = \frac{11.86}{(d + 12.56)^2} \frac{W}{cm^2}.$$

A plot of the the maximum power vs f(d)/f(0) is shown in Figure 5. As expected, the data follows a linear trend in f(d)/f(0). The deviations are possibly due to the effect of the light not being spread symmetrically about the bulb caused by the lamp shade. Effects of ambient light may also help to explain deviations.

Voltage U for Maximum Power Output
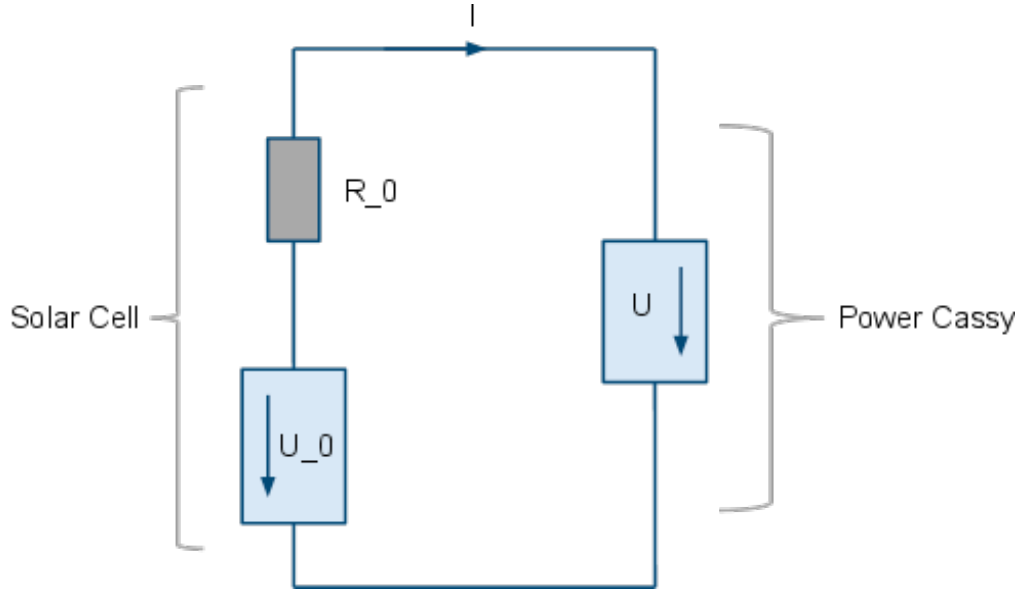
Figure 6. A simplified circuit model of the system studied.

For the circuit in figure 6, the power output at the load U is P=UI. We can consider the applied voltage of the Power Cassy as an equivalent resistance R which relates to I by U = IR. Then the effect at the load is P=UI=RI². With U_0 =(R+R_0)I, the current is I=U_0 /(R+R_0) and plugging this into the effect gives

$$P = R(\frac{U_0}{R+R_0})^2 .$$

Taking $\frac{dP}{dR} = 0$ to find the maximum gives, after some algebra, that $R = \pm R_0$. The negative value of $R = -R_0$, is excluded due to resistors being positive.

The voltage corresponding to R=R_0 becomes

$$U_{max} = R_0 I = R_0\frac{U_0}{2R_0} = \frac{U_0}{2}.$$

This means that when there is maximum power output at the load, the voltage U over it is half that of the voltage over the solar cell as seen in figure 4. For the curve obtained when the lamp is 4 cm from the cell, we get that $U_{max} \approx -0.3V$. Corresponding value of U_0 is found from figure 3 since when $I = 0$ we must have $U = U_0$. So we obtain from figure 3 that for lamp-to-cell distance of 4cm we have $U_0 \approx -0.57 V$, which agrees reasonably with $U_{max} = \frac{U_0}{2}$.

Maximum Efficiency of a pn-junction Solar Cell

In figure 7 a theoretical bound for the efficiency of a pn-junction solar cell is presented. On the x-axis the parameter x_g gives the ratio between the bandgap E_g of the energy k_BT where T is the

temperature of the black body emitting the light to illuminate the solar cell. The figure is taken from the compendium.
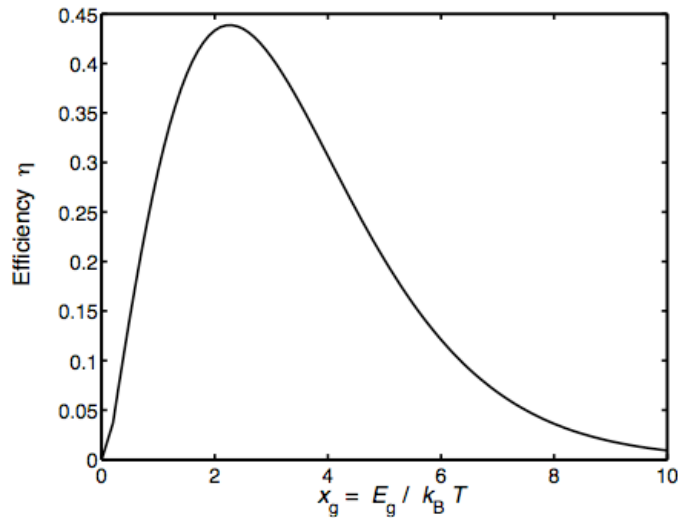

Figure 7: Upper limit of efficiency of pn-junction solar cell η at 0 K versus $E_g/(k_B T)$ where T is the temperature of a blackbody illuminating the solar cell and E_g is the band gap of the semiconductor..

The maximum efficiency of a solar cell is given at

$$\frac{Eg}{k_b T} \approx 2.3$$

.

Since the temperature of the sun is roughly 6000 K, the most efficient semiconductor material is one with an energy gap of 1.19 eV. Silicon has an energy gap of 1.17 eV (at T=0K, and 1.11 eV at T=300K) which means it is an excellent material to use in solar cells.

Say that a light bulb burns at a temperature of 3000K [1], approximating it by a black body we find that $x_g = E_g/k_b T = 1.11eV/0.259eV = 4.29$. From the graph we see that the upper limit of the efficiency of a pn-junction solar cell will be approximately $0.3 = 30\,\%$.

Approximating the spread of the light emitting from the light bulb to be spread over the surface of a sphere and the solar cell having approximate size 6 cm^2, the estimated fractions of photons hitting the cell is about 2.36e-4 at a distance of 45cm. Assuming a light bulb of 60 W, with a complete conversion of electrical energy to light and the maximum power being 2.03e-3 at this distance, the efficiency would be about 0.14=14%. This falls within the range of our theoretical maximum, and is thus considered a fair approximation.

Though there was a wide variety of calculated efficiencies ranging from ~3%, for the lower lamp-to-cell distances, to ~15% for the upper lamp distances, one possible conclusion is that

---

[1]http://hypertextbook.com/facts/1999/AlexanderEng.shtml

the sources of ambient light present in the room may have had too big of an impact on the experimental data obtained.

Note that the lamp shade actually renders the sphere-approximation insufficient due to the fact that the it focuses the light emitted from the source to a cone-like form.

Appendix: Structure of Computations and MATLAB Code

Regression to the Diode Equation
Using the following Matlab code a non-linear least squares regression is done in order to fit the diode equation to the collected data set.

```
>>format long
>>f=load('trinolight_use.txt');
>>U=f(:,2);
>>I=f(:,3);
>>initials=rand(1,2);
>>options=optimset('Display','iter');
>>params=fminsearch(@diode,initials,options,U,I);
```

where "diode.m" is defined by:

```
>>function err = diode(params,U,I)
>>Isat = params(1);
>>Vsat = params(2);
>>errVec = I-Isat*(1-exp(-U/Vsat));
>>err = sum(errVec.^2);
```

In the code there is a random choice of the input parameters, this has as an effect that the I_sat parameter varies within the order e-7 whereas V0 is unchanged.

References

Kittel, C. Introduction to Solid State Physics, 8th edition (2005).

The compendium describing this lab, Rickard Fors, IMIT/KTH, April 2005.

http://hypertextbook.com/facts/1999/AlexanderEng.shtml; 2011-04-21.