Physics 6180/7180:	Graduate Physics Laboratory
I Hysics 0100//1000	Graduate r hybres Eaboratory

Experiment	CM4:	Current-voltage curves in semiconductor diodes and solar cells
References:	1. 2	Kittel, chap. 8, pp. 216-221 (7th ed); S.M. Sze. The Physics of Semiconductors
	3.	E.S. Yang, <i>Fundamentals of Semiconductor Physics</i> , McGraw-Hill, New York, 1978
	4.	D.K. Schroder, <i>Semiconductor Material and Device Characterization</i> , Wiley, New York, 1990.
Goals:	-to stu -to stu	dy the current flow across interfaces between two dissimilar materials dy the case of n-p semiconductor junctions
	-to stu -to and genera	dy the case of metal-semiconductor junctions (Schottky barriers) alyze the results in terms of the electron and hole recombination and ation currents
	-to app	ply the results to the case of light-generated reverse currents in a solar cell
Equipment:	-Keith -xenor	ley 2400 Source meter (this and the simulator are located in MH 3014) h lamp solar simulator for air mass 1.5 simulation
	silicon	and CdTe solar cells

Background:

Read in Kittel, chapter 8, especially the major sections on **IMPURITY CONDUC-TIVITY and p-n JUNCTIONS**. The role of the Fermi energy is important to understand. Recall that the **Fermi energy** is technically the value of the **chemical potential at zero temperature**. However, the Fermi energy or Fermi level is often loosely treated as the chemical potential at all temperatures since in <u>most</u> semiconductors the chemical potential does not change much with temperature--at least up to about room temperature. Recall that both electrons and holes in a semiconductor obey Fermi statistics with the occupation probability equal to

$$f_e(\varepsilon, T, \mu) = \frac{1}{e^{(\varepsilon - \mu)/k_B T} + 1} \quad \text{and} \quad f_h(\varepsilon, T, \mu) = \frac{1}{e^{(\mu - \varepsilon)/k_B T} + 1}$$

where ε is the electron or hole energy (measured from the top of the valence band), T is the temperature, and $\mu = \varepsilon_F$ is the chemical potential (or loosely, the Fermi level). When one includes $g_e(\varepsilon)$, the density (per unit volume and per unit energy) of electron states in the conduction band and $g_h(\varepsilon)$ the density of hole states in the valence band, one obtains the density (per unit volume) of electrons in an intrinsic (undoped) semiconductor as

$$n = \int g_e(\varepsilon) f_e(\varepsilon, T, \mu) d\varepsilon = 2 \left[\frac{m_e k_B T}{2\pi \hbar^2} \right]^{\frac{3}{2}} e^{\left(\frac{\mu - E_g}{k_B T} \right)}$$
(3)

Similarly for the density per unit volume of holes,

$$p = \int g_h(\varepsilon) f_h(\varepsilon, T, \mu) d\varepsilon = 2 \left[\frac{m_h k_B T}{2\pi\hbar^2} \right]^{\frac{3}{2}} e^{\frac{\mu}{k_B T}}$$
(4)

In the equations above, the zero of energy is taken to be the top of the valence band. E_g is the energy gap between the top of the valence band and the bottom of the conduction band.

If so-called "shallow" impurities are added to the semiconductor, then the density of electrons and holes will be greatly modified. Shallow dopants are those which occupy states very near the extrema of either the valence band or the conduction band--i.e., energy difference less than kT at room temperature. Then for donors, the density of electrons is often about equal to the density of donor atoms and the density of holes may be nearly equal to the density of acceptor atoms. Although, of course, if both donor and acceptor impurities are added then some compensation will occur. Although in an "intrinsic" semiconductor (pure, with insignificant numbers of donors or acceptors) the Fermi level (ε_F) lies about mid-gap ($\sim E_g/2$), when donors are added the Fermi level resides between the donor level and the bottom of the conduction band. Similarly when acceptors are added, the Fermi level will lie just above the top of the valence band at low temperature. (Recall from Eqs. 1 and 2 that the chemical potential (\sim Fermi level) is the energy at which the occupation probabilities f_e and f_h are equal to 1/2.)

Even with this very brief and oversimplified summary it should be possible to understand the band bending which occurs when *n*-type and *p*-type regions are adjacent in a semiconductor. The situation is sketched below in Figure CM4-1, taken from E.S. Yang. When free charges (electrons or holes) are present in the two regions, electrons will flow from the n-type region where their energy is high to the p-type region where their energy can be much lower. This will leave the fixed donor atoms deficient of one electron and therefore positively charged. The electrons reaching the p-type side will recombine with holes to create negatively charged acceptor ions. This diffusion will continue until the resulting electric field is strong enough to inhibit further flow along the concentration gradients of electrons and holes. You should be able to convince yourself that the final result gives the band bending shown in the figure and that the final <u>electro</u>-chemical potential is constant throughout the semiconductor when no external bias is applied. In order for the final μ to be constant, however, the band banding must be roughly as shown.

In many situations, the *n*- and *p*-type regions have quite different doping densities, but approximately constant doping densities in each region. In those cases the junction conditions may be approximated as a "one-sided step junction." For this situation, the dopant densities, electric field, and potential are sketched in Fig. CM4-2 (also from E.S. Yang).

Although in equilibrium the net density of electrons and holes in the n-type and p-type regions is fixed, at finite temperature there is a small *recombination current* of electrons <u>up</u> the potential barrier into the *p*-type side. Similarly, at finite temperature, there is a *generation current* caused by electron-hole pairs which are thermally generated in the *p*-type region and the electrons slide down the potential ramp into the *n*-type side. Similarly there is a *hole recombination* current and a *hole generation* current. At equilibrium, however, these currents exactly balance so that there is no net flow across the junction.

In the approximation of the one-sided step junction, solution of the Poisson equation shows that there will be a region in the lightly doped semiconductor depleted of carriers. The width of this "depletion region" is shown to be

$$W = \left\{ \left(\frac{2\kappa\varepsilon_0}{eN_a} \right) \left(V_{bi} \pm V_A - \frac{2k_BT}{e} \right) \right\}^{\frac{1}{2}}$$

where κ is the dielectric constant, $\epsilon_0 = 8.8 \times 10^{-12} \text{ C}^2/\text{N-m}^2$, V_{bi} is the built-in potential (typically



Figure 4-2 (a) Isolated p-type and atype silicon before contact, (b) the energy-band diagram after contact, and (c) the space-charge distribution of (b).

about 2/3 of the band gap energy), V_A is the externally applied voltage, and N_a is the ionized charge density of acceptors in the p-type region. (If the lightly doped region is n-type, then replace N_a with the density of ionized donors, N_d.)

Fig. CM4-1



Fig. CM4-2



To understand current flow however, we need to understand what happens when a voltage is applied across the junction. The electron potential energy across a step junction under forward and reverse bias is sketched in Fig. CM4-3 (again from Yang's book).



Fig. CM4-3. Electron potential energies across a one-sided step junction (from Yang, Ref. 3).

It is especially important to understand the properties of the forward biased n-p junction. Fig. CM4-4 (from Yang) sketches the minority carrier distribution, the minority carrier currents, and the full electron and hole currents across the junction.

Finally, one may derive the total current across the junction. The result is sketched in Fig. CM4-5, from Yang, of course. The analytical expression for the current-voltage characteristic of the ideal n-p junction is given by (Eqs. 4-46, 4-47 in Yang):

$$I = I_n(0) + I_p(0) = I_0[exp(eV/k_BT)-1], \text{ where}$$

$$I_0 = eA[(D_pp_{n0}/L_p) + (D_nn_{p0}/L_n)].$$
(5)

This is the famous Shockley equation. Here, L_p and L_n are the hole and electron diffusion lengths, $L_n = (D_n \tau_n)^{1/2}$, etc, $D_{n,p}$ are the electron and hole diffusion coefficients, and p_{n0} and n_{p0} are the minority carrier concentrations far from the junction region. A is the area of the junction.





Figure 4-7 The forward-biased p-n junction: (a) minority-carrier distributions, (b) minority-carrier currents, and (c) electron and hole currents.

Fig. CM4-5



CM4-5

Solar cell performance

The case of a solar cell is very similar to that of a diode except that the light generates electron hole pairs both in the junction region itself and in the lightly-doped or intrinsic region which then diffuse to the junction region. As a result a large <u>reverse</u> current is generated which will shift the I-V curve in the negative current direction. Thus the shape of the I-V curve will resemble Fig. CM4-5 but shifted along the negative current axis.

Important parameters of the solar cell are V_{oc} the open circuit voltage, I_{sc} the short circuit current, and the fill factor. The fill factor refers to the "squareness" of the *I-V* curve in the fourth quadrant. The FF is the maximum power point of the *I-V* curve divided by $V_{oc}I_{sc}$.

$$FF = P_{max}/V_{oc}I_{sc} = I_m V_m/V_{oc}I_{sc}.$$

See Fig. CM4-6.



Fig. CM4-6: Typical current-voltage relation for a polycrystalline CdS (n-type) / CdTe (p-type) heterojunction solar cell fabricated at the University of Toledo. Measurement done at the National Renewable Energy Lab. V_{OC} =0.814 V, I_{SC} =3.5429 mA, fill factor=73.25%, AM1.5 efficiency = 14.0%.

Note: In Fig. CM4-5, the scale for the reverse current is much smaller than that for the forward current (typically μA or pA); the apparent slope discontinuity at the origin is not real.

Experiments:

- Measure the I-V characteristics of two light-emitting diodes (LEDs), one red and one green. WARNING: the LEDs cannot tolerate high forward current. Therefore, you should in software set the maximum current to be only 15 mA or less! For other diodes, a maximum current of 100 mA or more should be OK.
- 2. Measure the I-V curves also for two transistor diodes; note some identifying factor, such as the shape, model # if there is one, or other distinguishing features so we'll know which is which. Note that for transistors, the base-emitter junction behaves like a diode, so that's what you'll measure.
- 2. Take the dark and light I-V of two solar cells--one nanocrystalline Si cell and one CdTe cell fabricated (both fabricated at the U. of Toledo). The tungsten-halogen light source should be adjusted for approximately one-sun intensity. This can be done by using the calibrated Si solar cell placed at the position (laterally and vertically) of the sample to be measured, and adjusting the intensity so that the photocurrent reads as close to 24.5 mA as possible).

Analysis:

The equation given on page CM4-4 for the current-voltage relationship of an ideal diode is rarely met in practice. One reason is that the introduction of dopants into a semiconductor, to obtain n-type and p-type behavior, also introduces electron-hole recombination states which often lie energetically near the middle of the band gap. Furthermore, the ideal diode equation ignores finite series resistance in the diode. The result is that a realistic *I-V* characteristic is written as

$$I(V) = I_0 \left(e^{e(V - Ir_s) / nk_B T} - 1 \right)$$
(6)

This equation properly accounts for a series resistance (r_s) and an ideality factor (n).

In the case of a solar cell, there is a large light-generated reverse current, $-I_L$, and furthermore there may be significant current shunting which is modeled with a shunt resistance (r_{sh}) so that the final equation for diode current in a solar cell is

$$I(V) = I_0 \left(e^{e(V - Ir_s)/nk_B T} - 1 \right) - I_L + (V + Ir_s)/r_{sh}$$
⁽⁷⁾

Note that for a simple diode, if you neglect the series resistance, you can extract the ideality factor by making a semilogarithmic plot of $\ln(I)$ vs. applied voltage *V*. The slope of the line will be e/nk_BT . Refer to Fig. CM4-7 taken from Schroder p. 148.

For a solar cell, you can find I_L from the value of current at large negative applied voltage, assuming that the shunt resistance is not too small. (Actually, it is often possible to measure the shunt resistance from the slope of the *I* vs. *V* curve for negative voltage bias, on a linear plot.) Then if you plot $\ln(I+I_L)$ vs. *V*, you can obtain the ideality factor for the solar cell.

- A. For the diodes (red and green LEDs, and the other transistor-based diodes), plot ln(I) vs. *V* and obtain the ideality factor, *n*, of the diode. (Note that the ideal diode has n=1.) From the intercept at V = 0 obtain the prefactor, I_0 which is the reverse saturation current.
- B. For the two solar cells, nc-Si and CdTe,
 - -find the light-generated current, I_L ,
 - -find the ideality factor, n
 - -find the prefactor, I_0 , the reverse saturation current.

Fig. CM4-7: (from Schroder) Log(I) vs. V for diode with series resistance. The upper dashed line is for $r_s = 0$.



Reverse saturation currents:

Typically the temperature dependence of the diffusion coefficients, D, and lifetimes, τ , is weak (due to phonon scattering) and the main dependence of the I_0 is on the density of holes (electrons) in the *n*-type (*p*-type) side. These are exponentially sensitive to the band gap energy and to the temperature. In the limit of a one-sided step junction, only one of the terms of Eq. 5 comes in and the value of I_0 is given by

$$I_0 \sim exp(-E_g/kT).$$

Since the temperature was \sim 300 K for all of your measurements, you should readily be able to extract the band-gap dependence of I_0 , the reverse saturation current. This is the reason you have measured diodes constructed from several different materials.

For your information, the room temperature band gaps of these materials are:

Ge:	0.66 eV
Si:	1.12 eV
GaAs:	1.424 eV
AlGaAs:	(depends on the composition of Al)
AlAs:	2.16 eV
CdTe:	1.45 eV
nc-Si:	~1.2 eV

Note: the wavelengths of the LEDs would approximate their bandgap energies. Assume that the red one is about 670 nm, and that the green one is about 530 nm. We may be able to measure these in an upcoming lab, but until then perhaps you can estimate the band gap from the $I_0...$