

## Capacitance-Voltage (C-V) characteristics of a solar cell

**Aim:** The C-V measurement experiment of a solar cell is to study how the junction capacitance varies with applied reverse bias and to estimate the doping density as well as the built-in potential.

**Theory:** When a p-n junction is reverse biased, uncompensated acceptor ions in the p- side of the junction and an equal number of ionized donors on the n- side of junction form the space charge region. Since there are no mobile carriers in this region, only the free carriers at the edge of the depletion region can respond to the externally applied ac field. The junction thus resembles a parallel plate capacitor, whose capacitance is specified as

$C = \left( \frac{dQ}{dV_{DC}} \right) = \frac{\epsilon_0 \epsilon_s A}{x_d}$  where Q is the charge,  $V_{DC}$  is the applied reverse bias voltage, ' $\epsilon_0$ ' is the permittivity of free space and ' $\epsilon_s$ ' is the dielectric constant of the semiconductor, A is the area of the 'pn' junction. The depletion region width ' $x_d$ ' of a reverse biased junction with a constant doping density ' $N_d$ ' is given by

$$x_d = \left[ \frac{2\epsilon_0 \epsilon_s (V_{bi} + V_{DC})}{qN_d} \right]^{1/2} \quad \text{--- -- 1}$$

$V_{bi}$  is the built in voltage, q is charge or electron, From above two equations, one can write

$$\frac{1}{C^2} = \left[ \frac{x_d}{\epsilon_0 \epsilon_s A} \right]^2 = \left[ \frac{2\epsilon_0 \epsilon_s (V_{bi} + V_{DC})}{qN_d \epsilon_0 \epsilon_s A^2 N_d} \right] \quad \text{--- -- 2}$$

In the above equation (2),  $V_{DC}$  is the reverse voltage. By plotting  $1/C^2$  versus  $V_{DC}$ , doping density and built in potential can be determined.

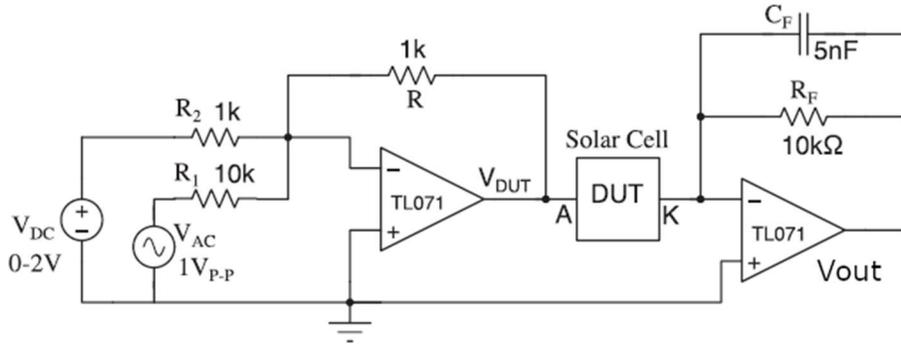


Fig.1 Circuit for CV data, where A is anode and K is cathode of solar cell(DUT)

The capacitance of the solar cell (Device under test, DUT) depends strongly on the applied DC voltage. Since the experiment involves measurement of the C-V profile of the capacitor, the circuit must also be designed to apply an additional DC voltage across the capacitor (solar cell) that can be varied, while measuring the AC current to extract the capacitance. In our setup, we apply a variable DC bias and a small AC signal (small enough not to perturb DC bias and not affect the charge polarization due to the DC bias) to the DUT. This is accomplished by using a basic inverting summing amplifier that adds the variable DC voltage (with unity gain  $R/R_2$ ) and the small signal AC voltage (with attenuation factor  $1/10 = R/R_1$ ), the output voltage of which is then connected to the DUT. The voltage  $V_{DUT}$  in Fig. 1 is thus given by the following equation:

$$V_{DUT} = -R \left( \frac{V_{DC}}{R_2} + \frac{V_{AC}}{R_1} \right) \quad \dots \dots \dots \quad 3$$

The AC voltage amplitude across the DUT (solar cell) is thus one tenth of the applied input DC voltage (smaller AC voltage can also be applied but we are limited by the sensitivity of our measuring instrument). One end (Anode, A) of the solar cell is connected to the output of the summing circuit while the other end (cathode, K) is virtually grounded due to negative feedback in the op-amp circuit. Current through a capacitor is proportional to the applied AC sinusoidal voltage. We use a transimpedance amplifier (I to V converter) so that the current flowing through the capacitor is converted into voltage, a multimeter. The transimpedance amplifier generates a voltage output that is proportional to the DUT capacitance ( $C_{DUT}$ ) and

$V_{DUT}$ . The magnitude of the **AC component of output voltage** is given by following equation:

$$V_{out} = V_{DUT} \frac{C_{DUT}}{C_F} \frac{1}{\sqrt{1 + \frac{1}{(\omega R_F C_F)^2}}} \dots \dots \dots 4$$

**Procedure:**

1. At very low frequencies (0.1 to 10 Hz) operational amplifiers exhibit 1/f noise but for fast operational amplifiers it can be up to 2 KHz, therefore, we only use high frequencies in this setup. Choose 5 KHz sine wave in the function generator.
2. In this lab we use 741 opamps instead of TL071 opamps.
3. Make the circuit as shown in Fig.1.
4. Applying AC voltage using function generator, Vary the DC voltage using DC power supply from 0 to 1.5 V in steps (positive supply from DC voltage will reverse bias solar cell in this case, why?) and record the  $V_{out}(AC)$  and  $V_{DUT}$  using separate multimeters. Derive equation 4. Using Equation 4, calculate  $C_{DUT}$ .
5. Plot  $C_{DUT}-V_{DC}$ . Estimate  $1/C_{DUT}^2$  for reverse bias voltages and plot  $1/C^2$  to extract  $V_{bi}$  and doping density. Choose the linear region in the plot of  $1/C^2$  versus  $V_{DC}$ .
6. Perform the experiment in dark condition (by covering the solar cell with a black sheet or keeping inside the table draw) and you try the same with light.

**Note:** Dielectric constant of Silicon (material of the solar cell) is 11.7, Area is the the complete area of the solar cell.

**References:**

- 1.American Journal of Physics 86, 787 (2018); doi: 10.1119/1.5052360
2. operational amplifiers noise: <https://www.analog.com/media/en/training-seminars/tutorials/MT-047.pdf>

3. Transimpedance amplifier: <https://www.allaboutcircuits.com/video-tutorials/op-amp-applications-current-to-voltage-converter/>