Implementation of One Diode Model Solar Cell Capacitance to Measure Temperature

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ABSTRACT

Solar panel power output is directly affected by the temperature of the solar panel. Solar panels are made up of solar cells which convert light into electricity.Spacecrafts in geostationary orbits and low orbits experience temperatures in the range of -180ºC to 80ºC depending on the orbit. Solar cells are mounted on honeycomb panels which are installed and Sun pointed in on-orbit operation. Solar panels charge batteries and supply power to the satellite during sun-light period and batteries supply power during eclipse period. The open circuit voltage (V_{oc}) of a silicon solar cell varies by about -2.5 mV/ ºC and temperature can bring about a dramatic change in the solar cell characteristic, particularly with reference to operating voltage. PRT mounted on the rare of the solar panel measure the temperature of the solar panel. This sets up errors due to temperature rise between solar cell blanket and solar panel and slow temporary response of PRTs. A method of using solar cell capacitance to measure the temperature of solar cell blanket is proposed. This removes error due to location and transient response of PRT. Solar cell as a temperature sensor for measurement of temperature is demonstrated and the results compare satisfactorily with the reported results.

Categories and Subject Descriptors
G.4 Matlab

General Terms
Algorithms, Performance

Keywords
Photovoltaic's, solar energy, solar cells, solar cell capacitance

1. INTRODUCTION

Solar energy is the main source of power for all Earth-bound satellites. The general schematic of a satellite power system is shown in Fig1. Solar cells are connected in series and parallel to get the required power to the desired voltage. These solar arrays charge batteries, apart from powering the payloads, during the sunlit period and batteries supply power to the satellite during the eclipse period. Power electronic modules regulate power flow at the required voltage and provide protection to the load and source. To derive maximum power the solar panels are pointed towards the Sun and tracked as the satellite moves around in its orbit. The solar energy is converted to electrical energy with an efficiency of 14-28 % depending on the type of cell used and how much the remaining energy heats up the solar panels. The temperature of the solar panel is decided by the stability between the Sun's incident radiations (1.35kW/m^2) (ESUN), the part of energy converted to electrical energy (E1) and the energy reemitted to cold space (E2)[1]

$$\text{ESUN} = \text{E1 (electrical)} + \text{E2 (heat)} \qquad (1)$$

If the electrical power generated is taken into the satellite and used, the power reemitted is E2 and if the electrical power is not used, it is also dissipated on the panel itself and the energy to be radiated is E1+E2. The temperature of the solar panel during the sun-light period will depend on the power to be reemitted (E2 or E1+E2) and the thermal emission characteristics of the solar panel and cells. The average temperature of a solar panel during the sun-light period is around 50ºC to 70ºC and during special processes, such as moving orbit operations; the solar panel temperature may reach as much as 100ºC. During eclipse, the solar panels do not receive sunlight and the temperature of the solar panels is decided only by the radiation of heat from solar panels to cold space which is at 4ºK (–269ºC) nominal. Depending on the period of the eclipse, the temperature of the solar panels reaches –55ºC to –180ºC.

2. METHODS OF MEASURING SOLAR CELL BLANKET TEMPERATURE

The temperature measurement of a solar cell blanket can be done by two methods. One is by using the external PRT which is mounted on honeycomb panels and the second method uses the equivalent circuit of the solar cell which comprises of a solar cell capacitance.

2.1 Platinum Resistance Thermometer

Measurement of solar array temperature is very important, which is continuously monitored to the ground station. It may be studied that the rate of change of temperature as the satellite goes into eclipse and come out into sunlight is large; about 25ºC to 15ºC/min. This leads to severe thermal pressure on the material used such as cell interconnects whose failure can lead to lowering of power generated. The solar cell performance is closely checked to ensure enough power is generated over its operating life of 10-20 years. To be able to estimate and forecast solar array electrical performance, its temperature must be known to a reasonable accuracy.

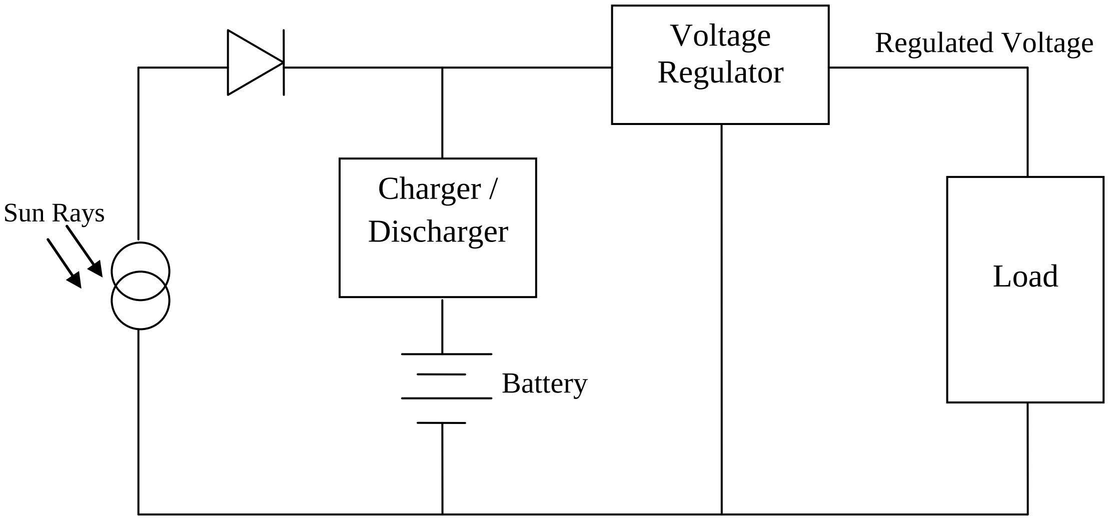

Fig 1: Schematic of satellite power system [6]

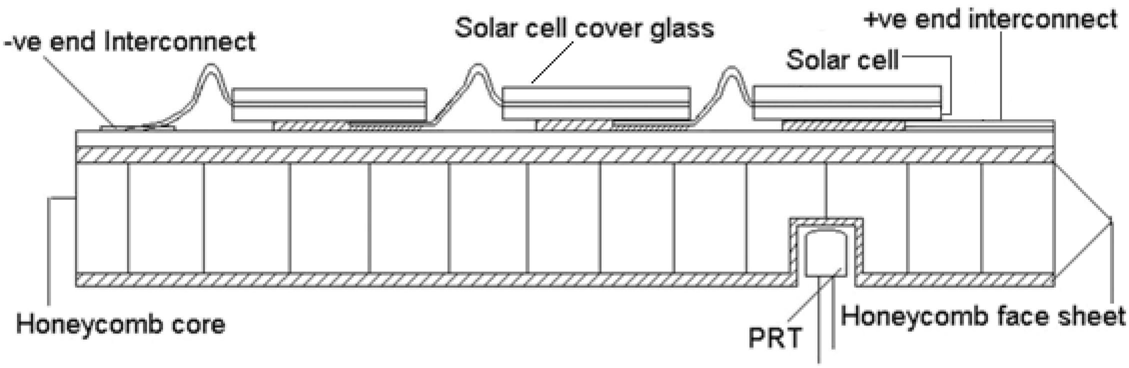

Fig 2: Location of PRT to measure solar panel temperature [6]

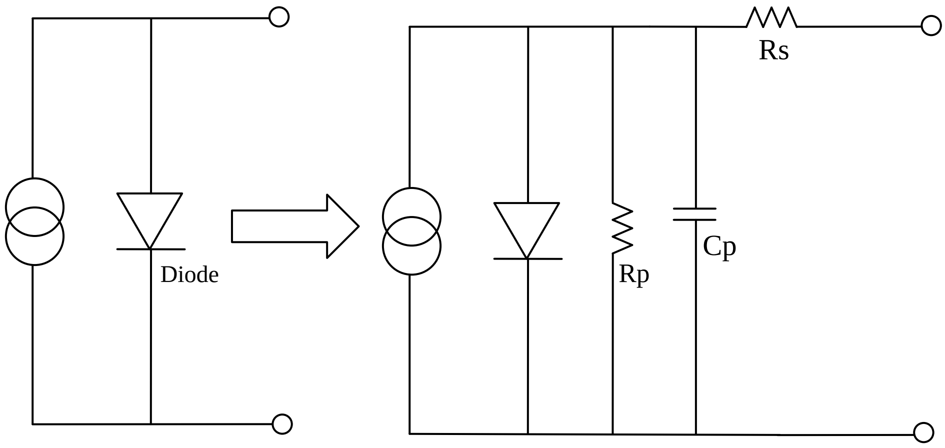

Fig 3: Solar cell electrical equivalent circuit [6]

In the current technology, the solar cell temperature is measured using 1000Ω platinum resistance thermometer in a wheat stone bridge. The PRT is placed in a hole drilled from the back of the honeycomb solar panel as shown in Fig2.

The solar cells are accumulated on the honeycomb panel using silicone bonding agent which is essentially a thermal insulator.Even though, the temperature evaluation can be good only in steady state and during conversion fromsunlight to eclipse the temperature evaluation is very difficult and flawed. At this stage it is necessary to differentiate between the temperatures of the solar cell blanket and the solar panel.The solar cell blanket is the top layer of the solar array consisting of solar cell and adhesive used for bonding cells on the panel. The temperature of attention is the cell temperature rather than the panel temperature. Under steady state, solar cell and panel temperatures differ by a fixed value due to thermal resistance of the bonding adhesive and the panel itself. However, if the temperature is varying with time, the relation between the two is more complex. The presently calculated steady state difference between cell and PRT temperatures is about 10ºC to 15ºC. So, it is necessary to measure the solar cell temperature as accurately as possible at all conditions which, until recently, was not possible. [2]

2.2 Solar Cell Capacitance

Capacitance measurements can serve to characterize a solar cell [9].The capacitance can be measured as a function of the DC voltage, frequency and time, doping concentration or AC voltage. Measuring the capacitance of a PV cell as a function of voltage can help when studying the doping concentration of the cell or the built-in voltage of the junction. The capacitance of the cell is directly related to the area of the device so devices with large areas will present large capacitances.

As the temperature is measured from solar cell characteristics itself, it represents very accurately its temperature under all conditions. Another advantage of using solar cell capacitance to measure its temperature rather than its open circuit voltage is the insensitivity of cell capacitance to magnetic field. Solar cell is a PN junction diode and can be modeled as a diode with a photo generated current source in parallel. The diode itself has shunt and series resistance as shown in Fig 3. The solar cell, like any diode, exhibits junction (C_j) and diffusion (C_d) capacitances.

The total cell capacitance (C_p) is the sum of the two capacitances [7]

$$C_p = C_d + C_j \qquad (2)$$

The diffusion capacitance C_d is generally dominant beyond V_d=0.8V_{oc}, which is an exponential function of the operating voltage, where V_{oc} is the open circuit voltage of the solarcell. The junction or transition capacitance is dominant over a voltage range of 0-0.7V_{oc} and in reverse bias. If the voltage range is confined to V_d< 0.7V_{oc} then the solar cell capacitance is given by its junction capacitance only.

3. EFFECT OF TEMPERATURE ON CAPACITANCE

The junction capacitance of a solar cell (any p-n junction) is given by a general formula.

$$C_j = \frac{B_0}{(V_0 - V_d)^n} \qquad (3)$$

$$|C_j| = \frac{I.\tau}{(V_0 - V_d)^n} \qquad (4)$$

Where, I = current, τ = carrier life time, C_j= junction capacitance, B_0 = a constant, V_d= applied bias potential, n = (1/2) diode factor.

Vo is a function of temperature and varies in a complex way depending on doping concentration [5].

$$V_0 = \frac{kT}{q} \ln \frac{N_D N_A}{ni^2} \qquad (5)$$

Where k = Boltzman constant; q = electron charge; N_D = doping concentration in n region; N_A = doping concentration in p region; n_i = intrinsic carrierconcentration.

Between 100K (-173ºC) and 350K (+80ºC),relation between $V_0$and T is nearly linear and can beexpressed as

$$V_0 = (B - mT) \qquad (6)$$

On the assumption that the solar cell is an abrupt junction pn diode, n= ½. As $V_d$is held constant and expanding the denominator, the solar cell capacitance can be expressed as

$$C_j = \frac{B_0}{(B - mT - V_d)^n} \qquad (7)$$

The variation of Cj with temperature can beapproximated to linear, quadratic, cubic or fourthpower function depending on the accuracy needed.Experiments are conducted to measure the solar cellcapacitance over a range of -180ºC to +80ºC.

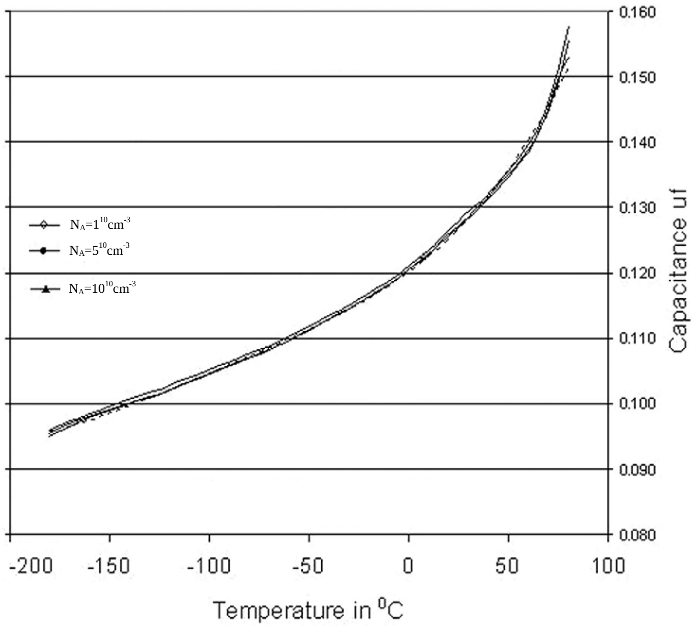

Fig 4:Changes in solar cell capacitance with temperature [6]

4. ADVANTAGES OF SOLAR CELL AS TEMPERATURE SENSOR

The results in Fig 4 show a solar cell could be used as a temperature sensor over a wide range of temperatures encountered by satellite solar panels. The major advantage of this method of temperature measurement is that the temperature sensor is located on the same side of the solar panel, mounted in the same way as any other solar cell [6]. So, no new technology is necessary for mounting the sensor or instrumentation. The sensor could be placed anywhere on the solar panel and its temperature accurately represents the solar cell blanket temperature which is the needed temperature. Even during quick temperature variation, as the satellite enters eclipse, the sensor experiences exactly the same variation as the power generating solar cells. This makes solar cell temperature measurement precise even during fast change in its temperature. This method could be used to map the solar panel temperature for very large panels. The solar cell capacitance is not responsive to magnetic fields, [3] which make this method ideal for temperature measurement in the presence of external magnetic fields. Several features such as self–calibration, nonlinearity correction, and temperature compensation are possible when a microcontroller is used to manipulate data. These features will improve the accuracy of measurement.

5. SIMULATION OF SOLAR CELL TO MEASURE TEMPERATURE

Numerical simulations using model equations in MATLAB is done.

These plots are plotted for the effects of changing temperature on various factors such as reverse saturation current (I_0), p-region doping concentration (N_A) for varying $V_d$and applied potential (V_d) for varying N_A.

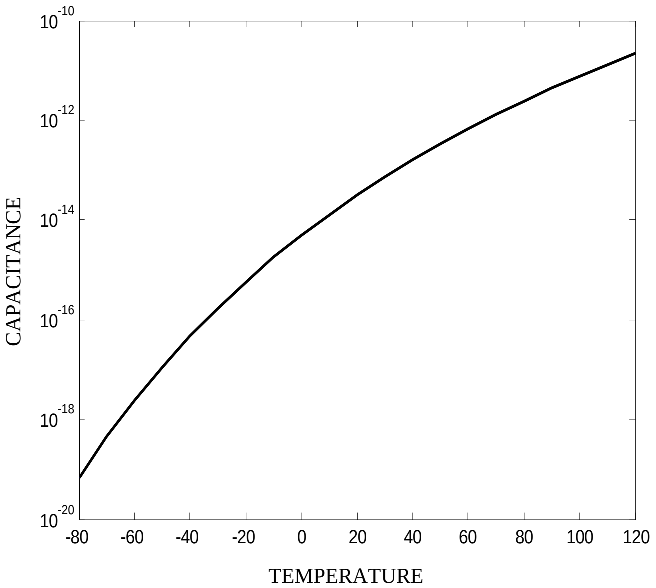

Fig 5: Plot for Reverse saturation current versus Temperature

5.1 Output: Reverse saturation current (I_0)versus Temperature (T)

When negative voltages are applied to the diode the current becomes constant at -I_0 as the exponential term in equation (8) quickly approaches zero.The current is independent of applied voltage once a small voltage magnitude is exceeded. This current is very small and is typically in the low nano-ampere region. The reverse saturation current is a strong function of temperature [8] as illustrated in Fig5.The plot shows a linear increase in reverse current on a logarithmic scale with temperature.

$$I = I_0[\exp(\frac{V_d}{nV_T})-1] \quad (8)$$

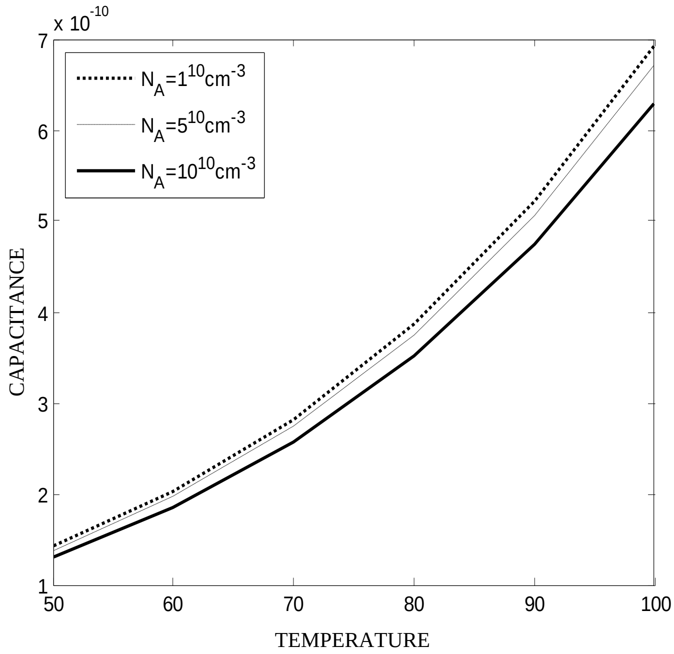

Fig 6 Plot for Capacitance (C_j) versus Temperature (T) for different N_A values

5.2 Output: Junction Capacitance (C_j) versus Temperature (T)

The plot in fig 6 depends on several parameters. To know the effect of temperature on capacitance, the value of bias voltage V_d is kept constant at 0.5V and the doping concentration of p-region N_A is varied.

The plot in fig 7 also shows the variation in capacitance with the change in temperature but here, the doping concentration is kept constant at $N_A=10^{10}cm^{-3}$ and the bias potential $V_d$is varied.

Table 1 shows the results for variation in capacitance with respect to temperature for V_d= 0.5V and varying N_A.

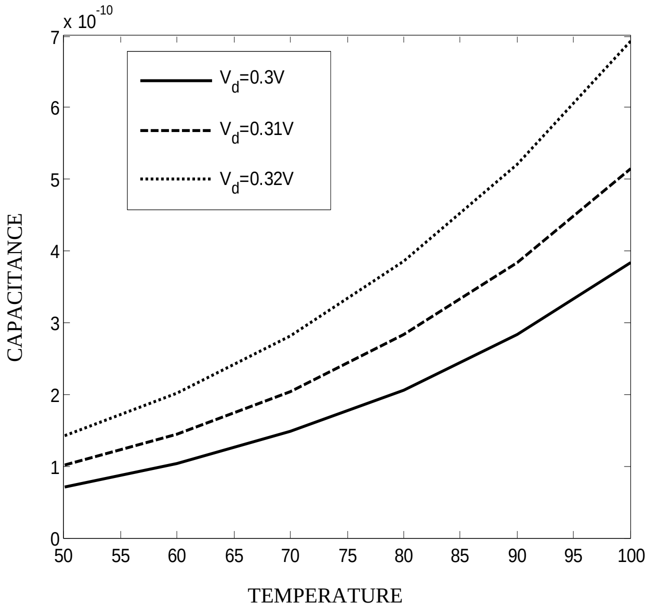

Fig 7: Plot for Capacitance (C_j) versus Temperature (T) for different $V_d$values

Table 1: Results for variation in capacitance with respect to temperature for V_d= 0.5V and varying N_A

Sr. No	Bias potential (V_d) at $N_A=10^{10}$	(T)	(C_j) (Farads)	Sensitivity (%)	Average sensitivity (%)
1	0.30V	55ºC	0.9×10^{-10}	61.1	59.85
		70 ºC	1.45×10^{-10}		
		85 ºC	2.3×10^{-10}	58.6	
2	0.31V	55ºC	1.25×10^{-10}	60.0	60.0
		70 ºC	2.0×10^{-10}		
		85 ºC	3.2×10^{-10}	60.0	
3	0.32V	55ºC	1.75×10^{-10}	60.0	60.35
		70 ºC	2.8×10^{-10}		
		85 ºC	4.5×10^{-10}	60.7	

We can observe that the capacitance increases for the rise in the temperature. The capacitance decreases for the decrease in the doping concentration. That is, more the doping concentration and temperature, more is the capacitance of the solar cell.

The sensitivity of the capacitance remains almost constant for change in doping concentration (N_A) of p region

Table 2 shows the results for variation in capacitance with respect to temperature for $N_A=10^{10}cm^{-3}$ and varying V_d.
We can observe that the capacitance increases for the rise in the temperature. The capacitance decreases for the decrease in the bias potential. So, more the bias voltage and temperature, more is the capacitance of the solar cell.

The sensitivity of the capacitance remains almost constant for change in the bias potential (V_d)

Table 2: Results for variation in capacitance with respect to temperature for $N_A=10^{10}cm^{-3}$ and varying V_d

Sr. No	Doping concentration (N_A) at V_d=0.5V	(T) (ºC)	(C_j)	Sensitivity (%)	Average Sensitivity (%)
1	10^{10} cm^{-3}	55	0.8×10^{-7} F	25.0	25.0
		70	1.0×10^{-7} F		
		85	1.25×10^{-7} F	25.0	
2	5^{10} cm^{-3}	55	0.78×10^{-7} F	25.6	25.05
		70	0.98×10^{-7} F		
		85	1.22×10^{-7} F	24.5	
3	1^{10} cm^{-3}	55	0.75×10^{-7} F	25.3	24.85
		70	0.94×10^{-7} F		
		85	1.17×10^{-7} F	24.4	

6. VERIFICATION

Table 3 shows simulated results for change in reverse saturation current (I_0) with respect to temperature (T) obtained using model equations in MATLAB which were compared with reference results as reported in [6] and [8]. The results compare satisfactorily with the reported results.

Table 4 shows simulated results for change in junction capacitance (C_j) with respect to temperature. The results show satisfactory comparison. The percentage error is found which can be reduced.

7. CONCLUSION

It has been shown that the solar cell capacitance can be used to measure temperature.This method of measuringsolar arraytemperature removes the issues associatedwith the useof PRTon the back of the panel. Reasonable accuracy can be achieved using a BSR silicon solar cell.

Table 3: Comparison of Reported [8] and Simulated I_0 v/s Temperature

Temperature	Current$|_{Vd=0.35V}$	
	Reported[8]	Simulated
-35ºC	2×10^{-12}A	5×10^{-12}A
10 ºC	50×10^{-12}A	10×10^{-12}A
65 ºC	4×10^{-9}A	1×10^{-9}A

Table 4: Comparison of Reported [8] and Simulated C_j v/s Temperature

Temperature	Current$|_{Vd=0.5V}$		% Error
	Reported [8]	Simulated	
50ºC	0.132µF	0.120µF	9.1%
60ºC	0.140µF	0.142µF	1.42%
70ºC	0.150µF	0.170µF	13.3%

8. REFERENCES

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