TESTING OF SPACE SOLAR CELLS AND SOLAR ARRAYS FOR SPACE APPLICATIONS

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ABSTRACT
The Power System of a Spacecrafts is the most vital system of a satellite, which has a major role in ensuring the complete success of the mission. Solar array meets the total power requirements of the spacecrafts during entire mission life. Solar array consists of number of solar panel substrates on which solar cells are laid down in series and parallel to generate the required power. The solar cells are either Silicon, GaAs/Ge or Multijunction. The paper presents a brief idea about the characteristics and testing of some of the most widely used Space Solar Cells.

KEYWORDS
Space solar cells, Solar arrays, Cell characterization

NOMENCLATURE

I_{sc} solar cell short circuit current
I_L load current
I_{ph} photo-induced current
r solar cell series resistance
V_{jd} solar cell diode voltage under dark
V_{jd} solar cell diode voltage under illumination
V_{mp} maximum power point voltage
V_{oc} solar cell open circuit voltage
V_t solar cell terminal voltage

1 INTRODUCTION

Solar panels are the key elements in the onboard satellite power subsystem and they provide the electrical power for operation of all subsystems and charge the batteries to use the power in eclipse period. Various type of solar cells and structural solar panel substrates of body mounted to large deployable solar arrays are used for meeting the power requirements of small satellites to big communication satellites.

1.1 THEORITICAL DESCRIPTION

1.1.1 SOLAR CELLS & SEMICONDUCTORS

Solar cell is the major cost deciding component of solar array. Solar cells are large area semiconductor diodes with the junction very near to the surface to facilitate the conversion of the energy in the shorter wave length regions. Solar cells directly convert light into electricity. Most of the energy in the sun's spectrum between 0.3 to 1.1 micron, even though other wavelengths are present. The free space sun-energy at 1 Astronomical unit distance from sun is 135.3mW/sq.cm. The direct conversion of sunlight into energy using solar cells is called the photovoltaic effect. Semiconductor materials are mainly group IV elements as their properties lie between those of metals and insulators. This is due to the energy gap required to push the electrons from valence band to the conduction band. This energy gap for semiconductors is midway to that of metals and insulators. Regions of semiconductors doped with donor impurities have an increase number of electrons in the conduction band at normal temperatures and are known as n-type materials. Those doped with acceptors are known as p-type. The most common Solar Cells are essentially just very large area p-n junction diode. Semiconductors can divided in to “direct” and “indirect” band gap types, depending upon the form of the relationship between the energy of electron in the conduction band and their crystal momentum[1].

The energy between the initial and final state is equal to the energy of the original photon:

$$E_f - E_i = hv \quad \text{Equation 1}$$

Where E_f and E_i are the final and initial energies, respectively.
In terms of electron momentum (p), the energy relation is:

$$E_f - E_c = p^2/2m_e \quad \text{Equation 2}$$

$$E_v - E_i = p^2/2m_h \quad \text{Equation 3}$$

Where m_e and m_h are the mass of electron and holes, respectively.

In case of an indirect band gap semiconductor, the minimum energy in the conduction band and the maximum energy in the valence band occur at different values of crystal momentum (p_0). In this case the transition occurs by two step process involving not only photons and electrons but also a third particle called **phonon.** As opposed to photons, the phonons have less energy but relatively high momentum.

1.1.2 AIR MASS STANDARDS

Total radiation from sun impinging above earth atmosphere is defined as AM0. The energy available (per unit area) is 135.3 mW/Cm^2. This is also known as one solar constant.Total radiation from sun passing through earth's atmosphere to the earth's surface, along earth-sun radius is defined to be AM1 (I=100mW/Cm^2).

1.1.3 SUNS RADIATION

The sun is a sphere of gas heated by a nuclear fusion reaction at its centre. Temperature near the sun's centre is around 20,000,000 K. Most of the intense radiation from the core is absorbed a layer of negative Hydrogen ions near the sun's surface. Temperature within the photosphere is much cooler than at the core but still very high to 6000K.This photosphere radiates continuous electromagnetic radiation closely like a black body radiation (at 5800 K). It covers all the wavelengths. The intensity corresponding to each wavelength varies corresponding to each wavelength varies as given by the Maxwell distribution. So the use of different solar cells depends upon their behavior for different wavelengths[1].

1.1.4 TYPES OF SOLAR CELLS

Space solar cells can be broadly classified as Single Junction Solar Cell and Multi Junction Solar Cells.In multi junction solar cells, we have 2 or 3 layers of different semiconductor one above the other.With only one semiconductor layer (as in single junction cells) the whole spectrum of the Sun cannot be covered. For example, Silicon gives a good response only in the wavelength region 400nm-1000nm. In order to exploit the various regions of solar spectrum, we use multi junction cells which utilise almost all the energy incident on it. Efficiency is also high in the case of Multi junction cells.

Type of solar cells depending upon material are Polycrystalline devices (Si – 8 to 10% , CdS/Cu_2S - 9% , $CdS/CuInSe_2$ - 12%) , Amorphous devices (Si - 5.5%) , Plastic Solar cells , Organic Solar cells , Quantum dot Solar cells , Nano Solar cells and Rainbow solar cells

1.2 WORKING OF SOLAR CELLS

The basic device requirement for photovoltaic energy is shown in figure 1. A p-n junction has required asymmetry. N-Type regions have large electron densities but small hole densities. Hence, electron flow readily through such material but holes find it very difficult. Exactly opposite is true for p-Type material. The inherent asymmetry encourages a flow of generated electrons from p-type region to n-type, and a flow of holes in opposite direction. When the illuminated p-n junction is electrically shorted, a current will flow in the short circuiting lead.

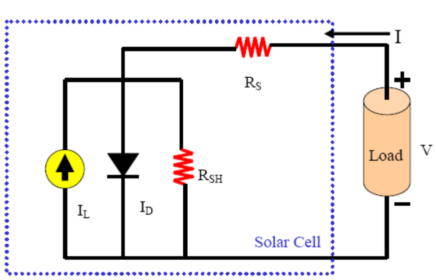

Figure 1: Schematic drawing of solar cell circuit

This light generated current is superimposed upon the normal diode-rectifying characteristics to give an operating region where power can be extracted from the cell.

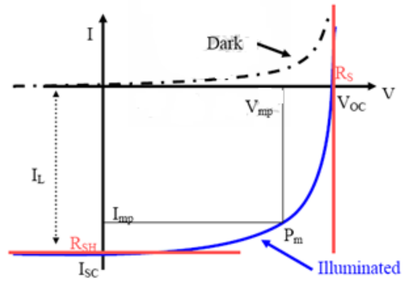

Figure 2: Operating region on characteristic curve

For our practical purposes, we take the mirror image of the characteristic curve as shown in figure 3.

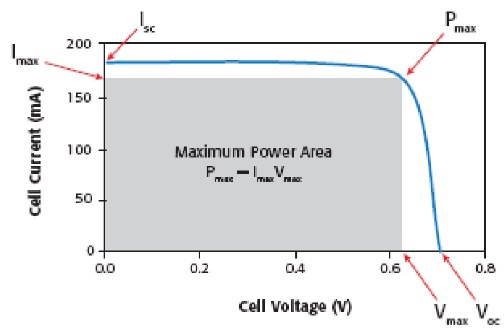

Figure 3 : Mirror image of characteristic curve

Series Resistance

$$I = I_{ph} - I_0\left(e^{\frac{q(V+IR_S)}{kT}} - 1\right) - \frac{V + IR_s}{R_p} \qquad \text{Equation 4}$$

1.3 PERFORMANCE OF SOLAR CELLS

The sun spectrum consists of various photons of different energy. The behavior of cells depend upon the energy content of the photons so different cells have different regions of wavelength where they give good response.

Spectral response is defined as short circuit current (I_{sc}) at a particular wavelength for a unit power. Spectral Response gives the richest information about the cell output at each wavelength.

SR= short circuit current / power incident Equation 5

Quantum Efficiency is defined as the number of carriers collected per incident photon at each wavelength. It is a quantitative measure of how many photons are converted in to electron-hole pairs. Spectral response and Quantum Efficiency are related as:

QE=number of electron output / number of photon input

Equation 6

1.3 SOLAR CELL PARAMETERS

1.3.1 SHORT CIRCUIT CURRENT (I_{sc})

Ideally this is equal to the light generated current. This is the current produced when there is no load voltage (V=0).

$$I_{sc} = I_{ph} = qAG(L_e + W + L_h) \qquad \text{Equation 7}$$

1.3.2 OPEN CIRCUIT VOLTAGE (V_{oc})

V_{oc} is determined by the properties of semiconductor mainly by band gap and its temperature dependence on I_0 (reserve saturation current).

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{I_{sc}}{I_0} + 1\right) \qquad \text{Equation 8}$$

1.3.3 SERIES RESISTANCE(R_S) & SHUNT RESISTANCE (R_{SH})

Series resistance is due to the combined effect of load resistance, wires and contacts etc. The shunt resistance is caused by leakage across the p-n junction around the edges of the cell and in non peripheral regions in presence of crystal defects.
Ideally: R_s=0 ohm and $R_{sh}=\infty$ ohm.

1.3.4 FILL FACTOR (FF)

At a particular point on I-V curve, we get the point of maximum power (P_{max}). Fill factor is the ratio of area of P_{max} point (V_{mp},I_{mp}) and total area.

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} \qquad \text{Equation 9}$$

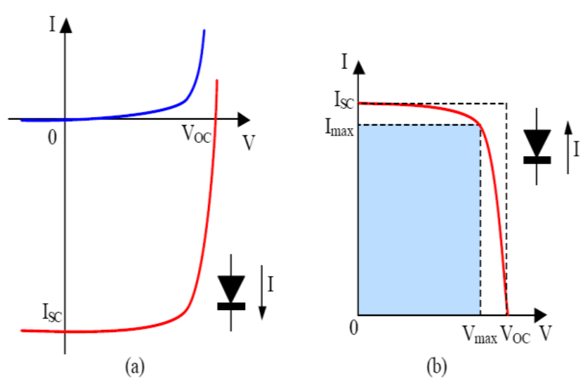

Figure 4 : I-V curve to calculate fill factor

1.3.5. EFFICIENCY (E)

Efficiency is given by;

$$\eta = \frac{V_{mp} I_{mp}}{P_{in}} = \frac{V_{oc} I_{sc} FF}{I * A} \qquad \text{Equation 10}$$

Where P is the input power given by the product of intensity and area of the cell.

2 TEMERATURE AND INTENSITY VARIATION

Intensity Dependence – Isc directly depends on Intensity while Voc varies logarithmically [1],[2].

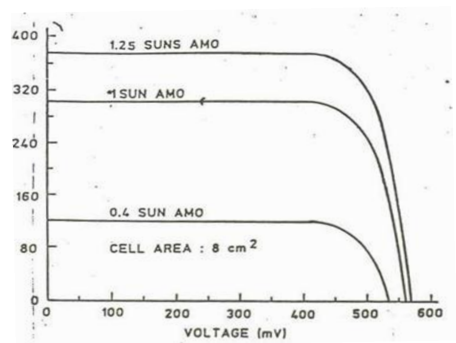

Figure 5: Temperature dependence of Isc

Temperature Dependence– dVoc/dtis>> dIsc/dt [1],[2].

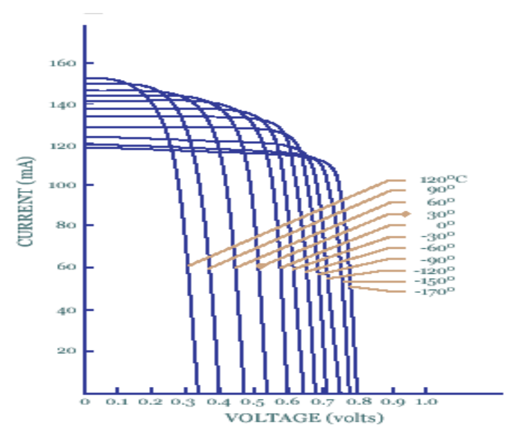

Figure 6: Temperature dependence of Voc

The series resistance Rs, can be determined from the I-V sweep at two or more light intensities [1],[2].

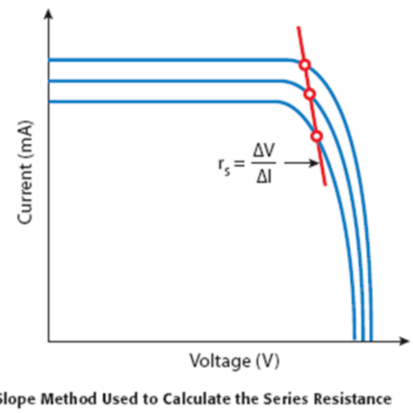

Figure 7 : Slope method for calculation of series resistance

Shunt resistance Rsh can be determined with the reverse I-V

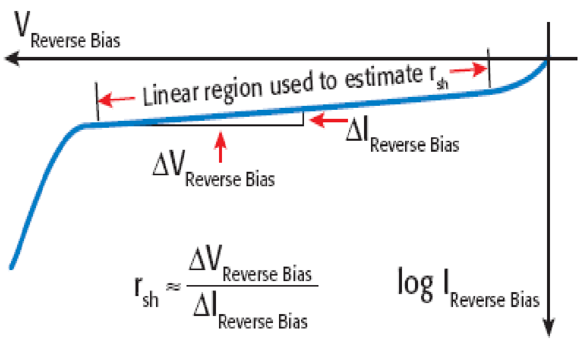

Figure 8: Reverse I-V curve to obtain Rsh

3 TESTING OF SOLAR CELLS

Solar cells are tested under a sun simulator with the help of Keithley cell tester.Cell is kept on a temperature controlled vacuum chuck.The sun simulator used in solar panels division contains Short arc **Xenon lamps** (T = 5800°K), which produces a spectrum closest to the sun spectrum. If necessary, suitable filters allow reaching the AM0, AM1 and AM1.5 specifications.A xenon arc lamp uses ionized xenon gas to produce a bright white light that is similar to natural daylight.

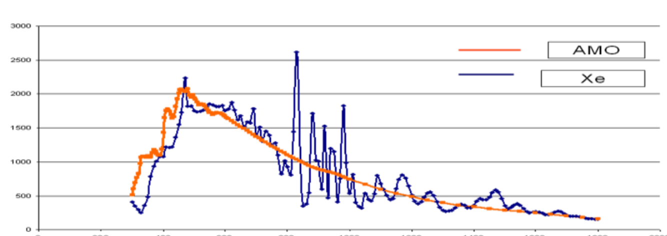

Figure 9 :Xenon Spectrum & AMO

Xenon lamps present a ray spectrum structure between 0.3micron and 1.5 microns , having unwanted spikes around 0.75 micron. Xenon spectrum contains lower energy in the higher wave length region, resulting into non-compliance with the sun spectrum. This problem has been tackled in the **Multi Source Sun Simulator.** The first source (ensuring the UV + VIS part) remains a Xenon lamp deprived of its IR parted by a low pass filter. The second source (ensuring the IR part) consists in a halogen lamp deprived of its VIS part by a high pass filter.

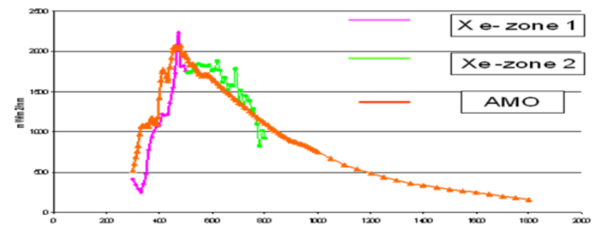

Figure 10 : Xenon Spectrum in multi source simulator from 300—800nm

4 TESTING OF SOLAR ARRAYS

All solar panel coupons and flight solar panels are being tested with this pulsed sun simulator. Light is flashed out by a pair of Xenon flash tubes and projected on a target plane 12 metre away from the source. Here also spectral irradiance should comply with AMO condition. Total flash time is around 2 milli-seconds. Mid 1 millisecond duration of light is approximately steady at which the solar cell string is loaded for measurement. A standard solar cell tracks the intensity level and a flash detector turns on the data acquisition unit with a delay to reach the threshold of the steady light level. The spatial & temporal uniformity is very good in this simulator.

Suitable electronic load is shunted across the string and loads from short circuit to the open circuit condition, leading to 60 different load points. Measured current points are then corrected with data collected by the standard cell. All these measurements are done in 1 milli-second. Solar panels are characterized electrically with the sun simulator at different stage like fabrication, thermovacuum cycling etc and the repeatability is ±1%. The effective black-body temperature of the xenon flash-lamps is a reproducible function of current density in the discharge volume. The plasma resistivity of linear xenon flash-lamps is a function of current density within the lamp. The lamp resistance and lamp current are functions of current density and lamp geometrical properties. The current density is controlled in order to control the color temperature. After accomplishing this power and voltage are uniquely determined by the length and bore of the lamp. At high current densities, lamp efficiencies of 65 to 75 % are obtained.

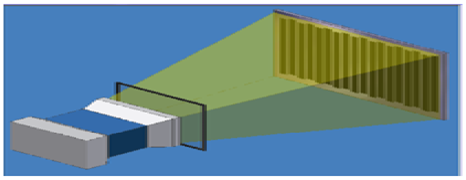

Figure 11 : Large area pulse solar simulator (lapss)

5 EXPERIMENTAL RESULTS

5.1 DATA PLOTS OF THE EXPERIMENTS CONDUCTED ON FOUR TYPES OF SOLAR CELLS

1. ATJ (Advanced Triple Junction)
   Cell dimension : 4cm x 7cm
2. ITJ (Improved Triple Junction)
   Cell dimension : 4cm x 7cm
3. Silicon Cell
   Cell dimension : 4cm x 6.5 cm
4. Gallium Arsenite
   Cell dimension : 2cm x 4.5cm

1. ATJ CELL CHARACTERISTICS

Total three ATJ cells were taken for the experiment, and their I-V & P-V characteristics were plotted by keeping them under X-25 Sun Simulator for AM 0 condition.

Temperature: 29.3˚C

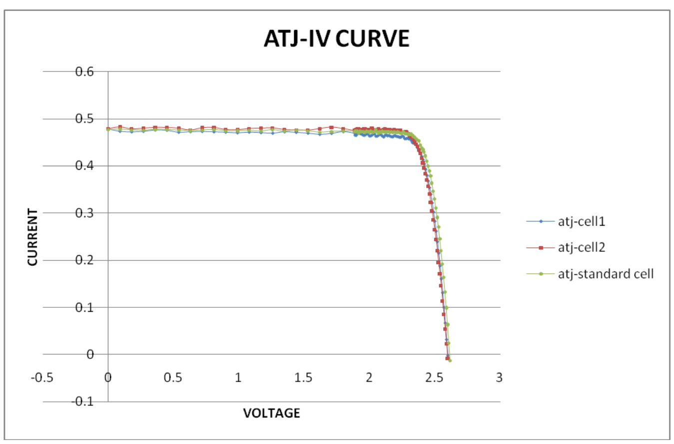

Figure 12: ATJ cell 1,2 & standard cell IV curve

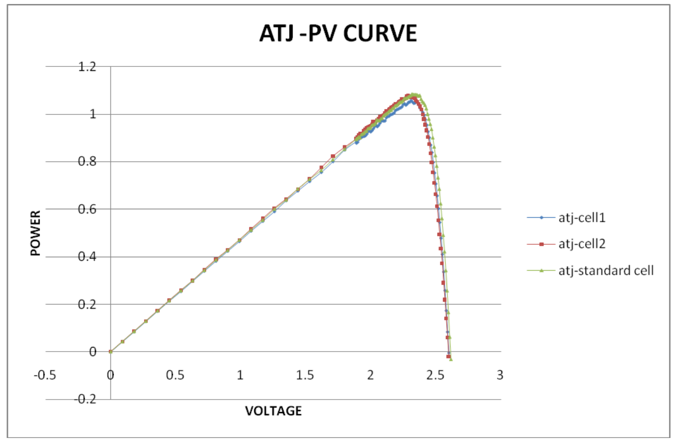

Figure 13: ATJ cell 1,2 & standard cell PV curve

2. ITJ CELL CHARACTERISTICS

Total two ITJ cells were taken for the experiment, and their I-V characteristics were plotted by keeping them under X-25 Sun Simulator and varying the lamp intensity.

Lamp Current: 75A, 84A, 93A

Temperature: 29.3˚C

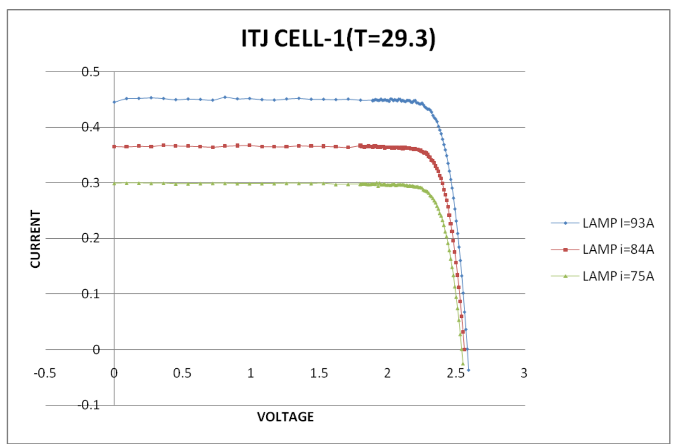

Figure 14: ITJ cell 1 IV curve under lamp cirrent 75A,84A,93A

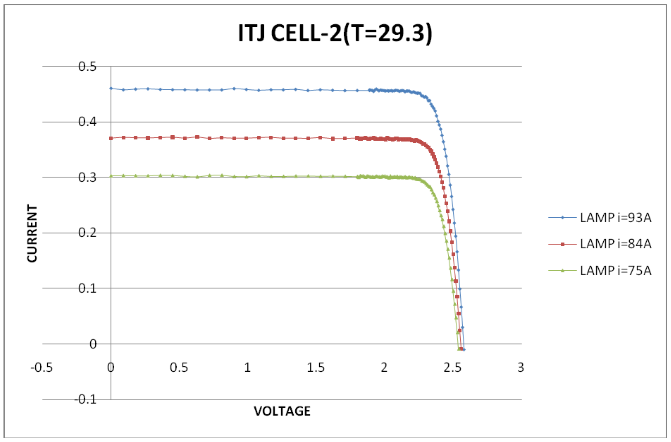

Figure 15: ITJ cell 2 IV curve under lamp cirrent 75A,84A,93

3. SILICON CELL CHARACTERISTICS

Total four SILICON cells were taken for the experiment, and their I-V characteristics were plotted by keeping them under X-25 Sun Simulator and varying the temperature.

Lamp Current: 94A

Temperature: 22.5˚C, 25.5˚C, 28.5˚C, 33.5˚C

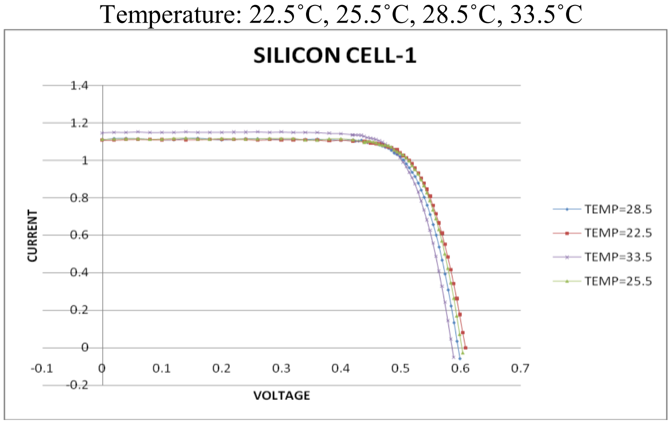

Figure 16: Silicon cell 1 IV curve at varying temperature

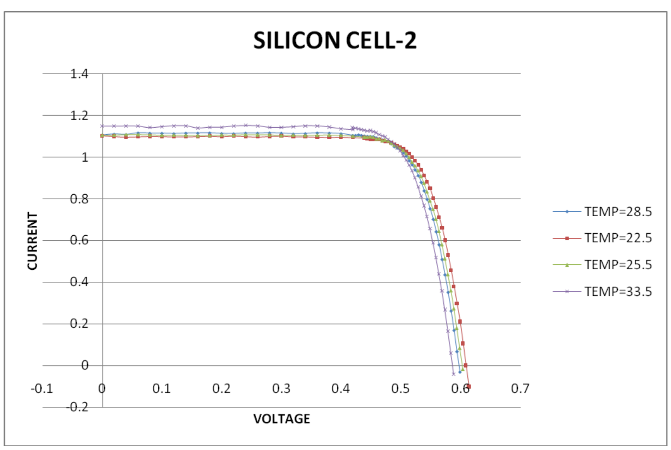

Figure 17: Silicon cell 2 IV curve at varying temperature

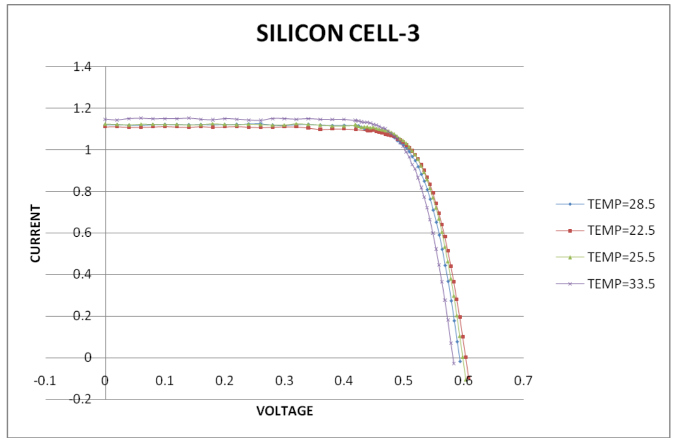

Figure 18: Silicon cell 3 IV curve at varying temperature

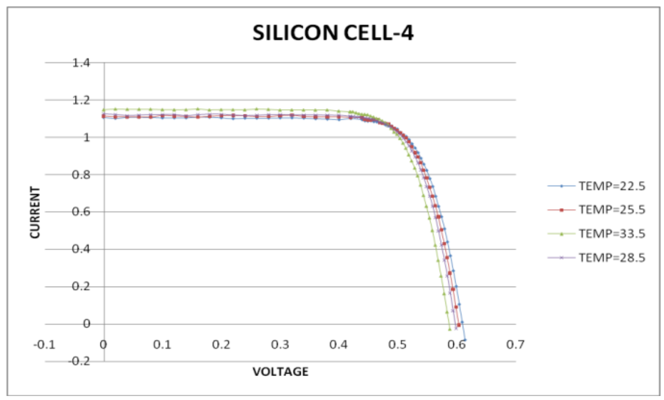

Figure 19: Silicon cell 4 IV curve at varying temperature

3.1 Voc Vs Temperature Graph for the four SILICON cells at 28.5°C

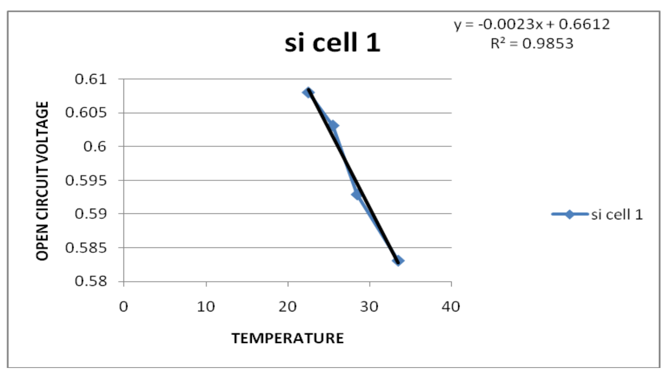

Figure 20 : Voc Vs Temperature Graph for the silicon cell 1

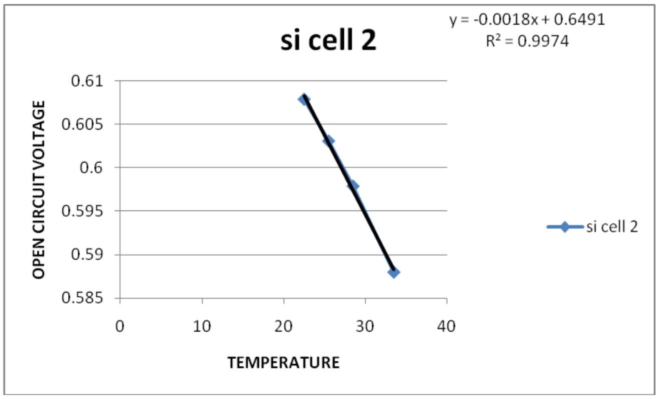

Figure 21 : Voc Vs Temperature Graph for the silicon cell 2

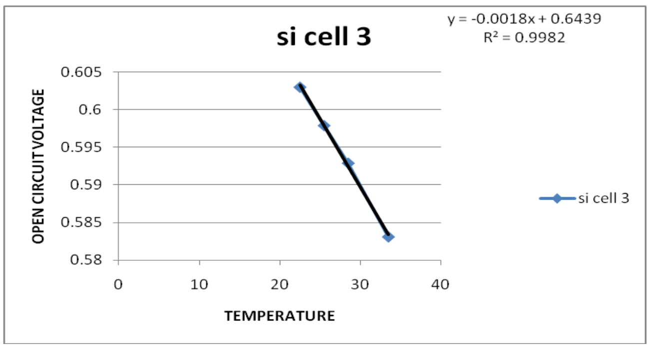

Figure 22 : Voc Vs Temperature Graph for the silicon cell 3

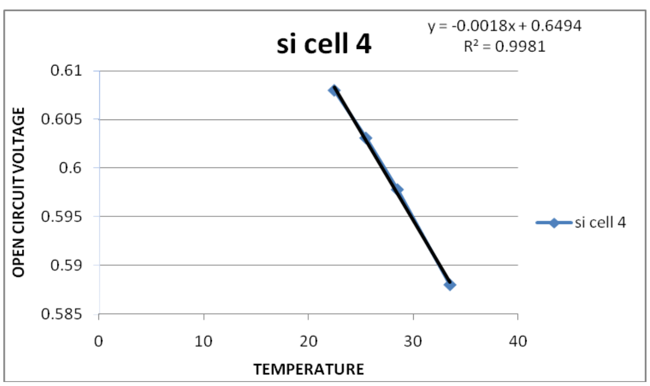

Figure 23 : Voc Vs Temperature Graph for the silicon cell 4

1. GaAs CELL CHARACTERISTICS

Total two GaAs cells were taken for the experiment, and their I-V characteristics were plotted by keeping them under X-25 Sun Simulator and varying the temperature.

Lamp Current: 92A

Temperature: 22˚C, 24.9˚C, 28˚C

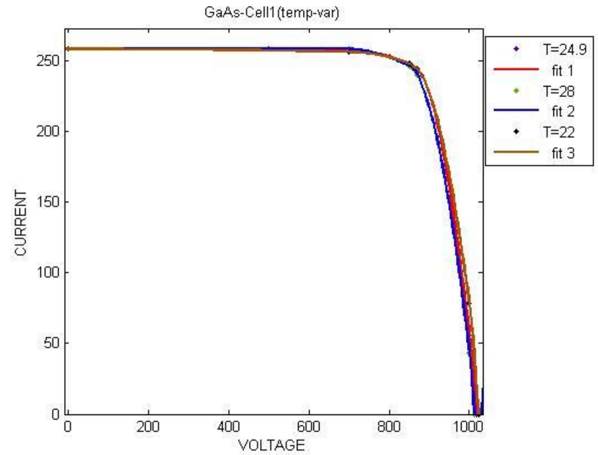

Figure 24 : IV curve for GaAs cell 1 at variable temperature

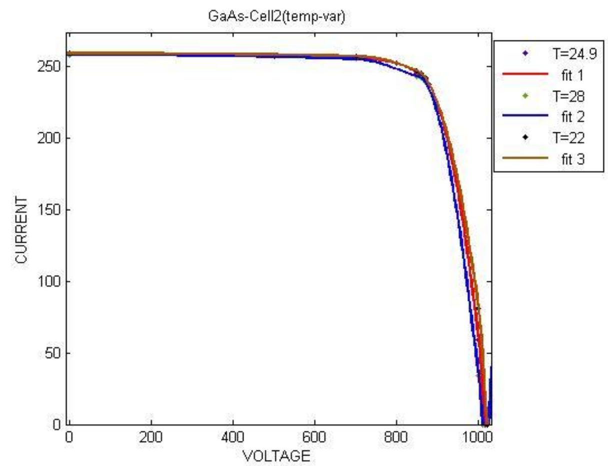

Figure 25 : IV curve for GaAs cell 2 at variable temperature

Temperature Coefficient

Cell 1: $\beta_{v\ oc}$ = -1.723

Cell 2: $\beta_{v\ oc}$ = -1.7231

Temperature (^{o}C)	R_s Cell 1:	R_s Cell 2:
22	-0.259	-0.294
24.9	-0.254	-0.303
28	-0.285	-0.279

Table 1 : Series Resistance GaAs cell 1& 2 at variable temperature

CONCLUSION

The concepts involved in space solar cell testing are elucidated. The various factors affecting performance are identified and the test results provided in form of graphs. The ATJ and ITJ cell characteristics at various temperatures plotted in figure 12,13,14,15 show the dependence of current and voltage as per the ideal expectations as elucidated in the theory.The silicon cell characteristics at four different temperatures are plotted in figure16,17,18,29.These plots are in excellent agreement with the expected behavior, the same can be used for extrapolation to obtain an idea of the characteristics at other temperatures. In addition the Voc vs temperature graphs are also presented in figures 20,21,22,23.The GaAs cell characteristics are provided in figure 24,25.The resistance value for the same is also presented in table1.The provided characteristics act as an guideline as various combinations of temperature are simulated and correspondingly various parameters have been calculated.

FUTURE SCOPE

In order to ensure the proper working of all the electronic gadgets present within a spacecraft, it is essential to maintain proper power supply by solar cells. Very high accuracy is needed in the design and implementation of power generation by solar cells. Power systems of spacecraft plays very vital role in ensuring the success of a particular mission. Mass minimization is the major challenge in the field of power systems. As the size of satellite is getting reduced the space and mass available is also getting reduced. So apart from the conventional power systems , it is important to develop some advanced solar cells, which may have less mass but have high efficiency power generation.

REFERENCES

[1] H.S. Rauschenbach, "*Solar Cell Array Design Handbook*"; Van Nostrand Reinhold Company,1980, pg:1-200

[2] Martin a Green,"*Solar Cell :Operating Principle Technology & System Application*" ; Prentice Hall; New Jersey