Chapter 1

INTRODUCTION

1.1 Motivation

Energy and fresh water are the two major commodities that furnish the fundamentals of every human activity for a reasonable and sustainable quality of life. Energy is the fuel for growth, an essential requirement for economic and social development. At the moment fossil fuels and nuclear energy are the main energy sources. However this form of energies is based on limited resources and produces harmful emissions. This classical energy sources cannot provide us with enough energy for the future any more. One problem is that the resources are limited. The stock of carbon-based fuels will be exploited in roughly 50 years. Another big problem is that carbon dioxide, the final product of burned fossil fuel, is known to influence earth climate significantly. Nuclear energy has always been subject of intensive public discussion due to the security and health risks of nuclear power stations and the following problems with radioactive waste. Therefore the transition from the fossil energy sources to the clean and renewable energy sources is at present one of the greatest challenges for the mankind.

Solar energy is the most ancient source and the root for almost all fossil and renewable types. Special devices have been used for benefiting from the solar and other renewable energy types since time immemorial. Solar irradiation energy is an abundant and widely available source of energy. The solar light can be directly converted into electricity by the photovoltaic cells. During its operation, a solar cell does not produce any emissions or noise. Therefore photovoltaics, is a very promising technology in satisfying the future demand for the environmentally friendly energy in a sustainable way. The many advantages of photovoltaics lend it to be the ultimate energy source.

In planning for the future scaling-up of photovoltaic power generation it is important to carefully choose the semiconductor material of which the solar cells are to be made. Important criteria for the choice are the maximum achievable efficiency on the other hand; it should be economic and ecological. These become even more important if one considers in future covering large areas with solar modules. A first category relates to the availability of the raw material as well as to the nature of the production technology used; these two factors determine the feasible minimum costs of solar cells. A second category are environmental and safety aspects; thus some of the candidates that are very promising from the efficiency point of view contain highly toxic elements (As, Cd, etc.) and one must consider it a problematic choice to cover substantial areas of the world’s surface with them. Considering all this, only material which is abundantly available in the earth’s crust, non-toxic and which have already reached technological maturity is silicon. So, silicon based solar cells are most suitable for the worldwide production of solar cells.

To design solar cells one need to understand the operation of these devices and numerical modelling has proved to be a valuable tool in understanding the operation of these devices. There are several numerical solar cell simulation programs in use. The importance of modelling and simulating the performance of solar cells cannot be overemphasized. Building a solar cell and testing it to determine if it performs as desired is too expensive and time consuming, especially considering that this process may have to be repeated numerous times until a solar cell is built that produces the desired results. Today, there are numerous solar cell programs developed by researchers from all over the world and there are also commercial simulation tools that can do solar cells modelling such as Silvaco, Crosslight etc.

1.2 Objective of this Study

The main objective of this thesis is to study how the efficiency of single junction silicon solar cell will be affected by the various parameters such as doping concentration, junction depth, ARC coating with texturing, series resistance etc. So that the effect of each parameter on the efficiency can be understood clearly and an optimised cell structure of higher efficiency can be achieved.

1.3 Thesis structure

This section briefly outlines the contents of the each chapter. The dissertation is organized into four chapters. A list of all reference sources consulted is given at the end of this dissertation.

- **Chapter 1** deals with the Introduction, objective of the thesis and organization of the thesis.
- **Chapter 2** deals with the detailed theory of the single junction silicon solar cell, which includes the equations used in modelling the cell, main parameters affecting the solar cell, and finally the methods to enhance the efficiency of the solar cell.
- **Chapter 3** deals with the approach to MATLAB coding i.e. how the code for single junction silicon solar cell is written in the MATLAB and how the various equations are linked with each other.
- **Chapter 4** deals with the simulation of single junction silicon solar cell which includes variation of different parameters such as short circuit current density, open circuit voltage etc. with doping concentration and junction depth, it also deals with the simulation of cell with ARC coating and texturing, resistive losses, variation in p+ layer (*keeping cell thickness constant*), and different cell thicknesses. Finally the simulation result of an optimized cell structure is presented.
- **Chapter 5** Conclusions and future efforts needed for this work are presented.
- **Appendix A** values of absorption coefficient, Reflectance, solar irradiance AM1.5G, refractive index of silicon, with different wavelengths.

- **Appendix B** source code in MATLAB for simulation of single junction silicon solar cell.

Chapter 2

SOLAR CELL DESIGN AND MODELLING

This chapter is divided into six sections; first section explains the working of a single junction solar cell. Second section explains the input parameters which are needed to model a single junction silicon solar cell. Third section explains all the important parameters such as short circuit current, spectral response etc. along with the related equations, which are important to clearly understand the photo-response of a solar cell. Fourth section explains the methods needed to enhance the solar cell efficiency. The next section explains series and shunt resistances of the cell and how they can be minimised. In the last section the schematic of the solar model along with the I-V equation of the cell are included.

2.1 WORKING OF SOLAR CELL

Solar cells convert solar energy, in the form of electromagnetic radiation, into electrical energy. A standard solar cell is shown schematically in figure 2.1. Sunlight is incident on the surface covered by a metallic grid acting as an electrical contact. Between the grid lines photons are absorbed in a semiconductor which is covered by an anti-reflective coating to reduce reflection. Photons with energies larger than the band gap E_G of the Semiconductor excites electrons from the valence band to the conduction band, resulting in free charge carriers; electrons and holes. The charge carriers are separated by either a gradient in the charge carrier density or an electric field. In figure 2.1 the charge carriers are separated by the electric field across the p-n junction and the electrons are transported through a load in the external circuit where they do work.

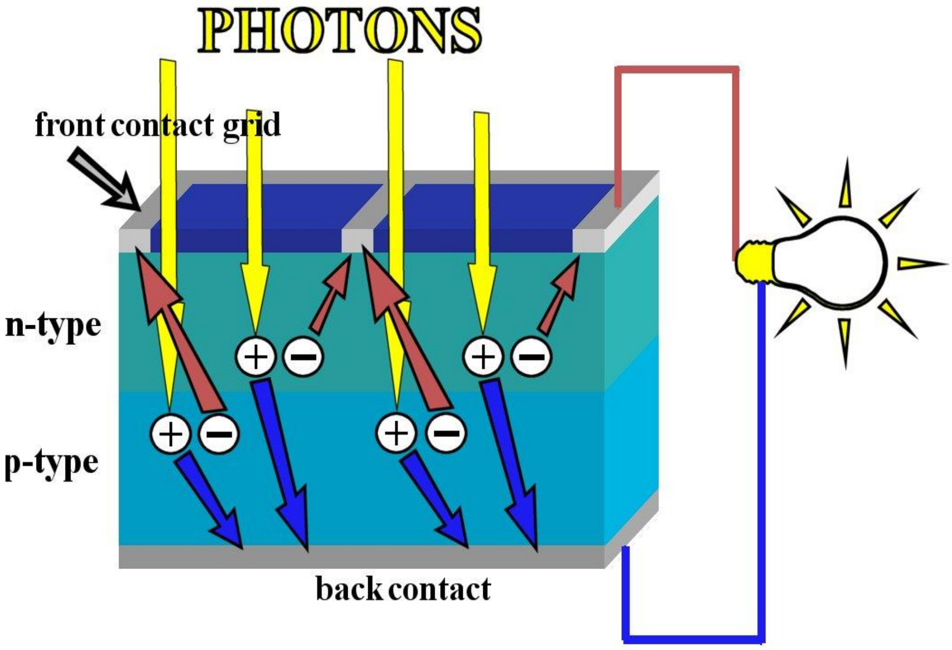

Figure 2.1: Structure of a standard solar cell

The analysis of the solar cell is complex. As it consists of different regions i.e. emitter, base, and depletion regions, the photons of different wavelengths are absorbed in the different regions depending upon the absorption coefficient at that wavelength. So to analyse the different parameters of the solar cell one needs to relate the absorption coefficient, reflectance, Drift-diffusion parameters (*such as carrier lifetimes*, *and mobility*), solar spectrum and surface recombination velocity, to determine the carrier generation and carrier separation in different regions. If the carriers are generated within the depletion region, they are separated by the electric field; they also can be generated in the regions away from the depletion region, in such cases there will be diffusion of the charge carriers, which results in different current components based on their respective regions of generation. So generation of carriers and its collection by the junction will decides the light generated current components in the solar cell. Adding all these current components will give the total short circuit current which is then used to further calculate the QE, SR, Voc etc. as described in the following sections.

2.2 PARAMETERS EFFECTING THE SOLAR CELL RESPONSE

The input parameters which are needed to model the single junction silicon solar cell are:

1. Absorption coefficient, which depends on the value of the bandgap of the semiconductor and the nature i.e. direct or indirect.
2. Reflectance of the semiconductor surface, which depends on the surface finishing, shape and antireflection coating.
3. Junction depth of the solar cell.
4. Drift-diffusion parameters such as carrier lifetimes, and mobility for electrons and holes which controls the migration of carrier towards the collecting junction.
5. Surface recombination velocities at the surfaces of the solar cell where minority carriers recombine.
6. Standard solar spectrum model used or the e.g. AM1.5G, AM0 etc.

2.2.1 Absorption coefficient α(λ)

As can be seen the absorption coefficient can take values over several orders of magnitude, from one wavelength to another. Moreover, the silicon coefficient takes values greater than zero in a wider range of wavelengths than GaAs or amorphous silicon. The different shapes are related to the nature and value of the bandgap of the semiconductor. This fact has an enormous importance in solar cell design because as photons are absorbed according to Lambert's law:

$$\Phi(\mathrm{z}) = \Phi(0)e^{-\alpha z} \qquad \ldots 2.1$$

If the value of α is high, the photons are absorbed within a short distance from the surface, whereas if the value of α is small, the photons can travel longer distances inside the material. In the extreme case where the value of α is zero, the photons can completely traverse the material, which is then said to be transparent to that particular wavelength. For example, silicon is transparent for wavelengths in the infrared beyond 1.1 micron approximately. Taking into account the different shapes and values of the absorption coefficient, the optical path length required inside a particular material to absorb the majority of the photons comprised in the spectrum of the sun can be calculated, concluding that a few microns are necessary for GaAs material and, in general, for direct gap materials, whereas a few hundreds of microns are necessary for silicon.

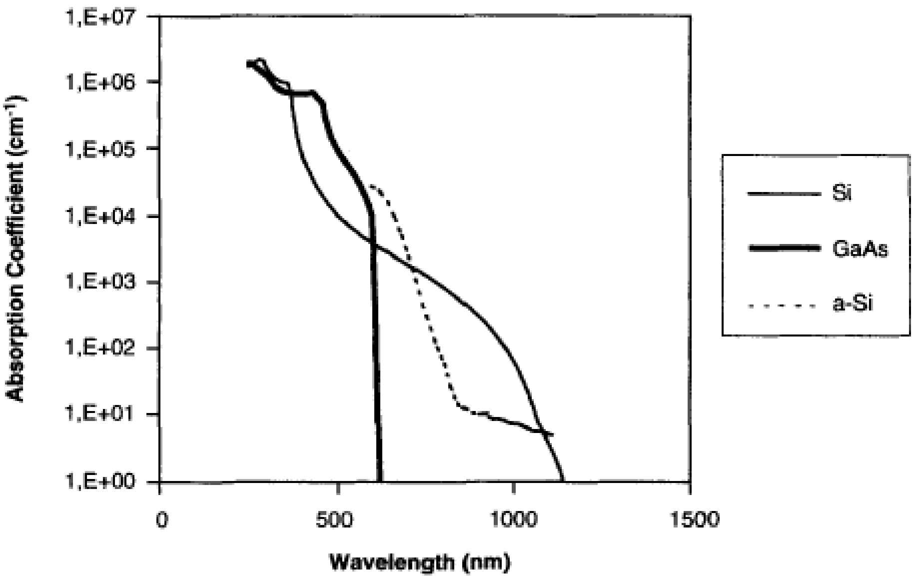

Figure 2.2 Absorption coefficient for silicon, GaAs and amorphous silicon as a function of the wavelength

So the absorption coefficient depends on the type of material used (*which is silicon in this work*) and is spectral dependent. It also depends on the optical confinement technique (*i.e. texturing*) used, which is discussed in the later sections.

2.2.2 Reflectance R(λ)

The reflectance of the solar cell surface is spectral dependent. As seen in the figure below the bare silicon has a high value of reflectance i.e. a significant amount of light will be reflected from the surface this can be minimised by using ARC coatings on the surface.

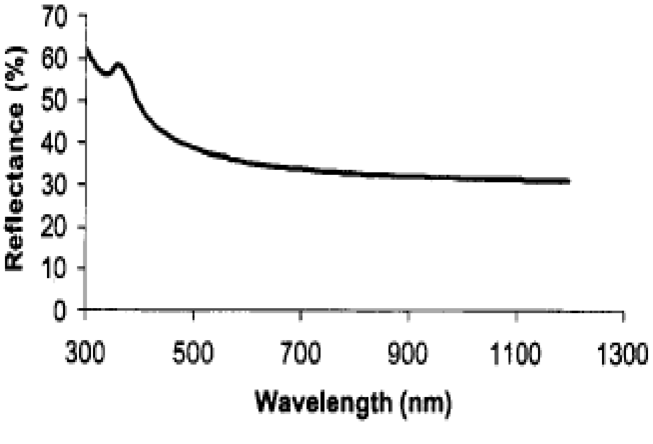

Figure 2.3 Reflectance of bare silicon surface

2.2.3 Junction depth

The carriers generated within the depletion region are separated by the electric field. The electric field in the depletion region is so high that nearly all the light-generated carriers within the depletion region are swept out of the depletion region before they can recombine. So all the carriers generated within the depletion region contributes to current hence the collection probability is unity at the junction. Away from the junction, the collection probability drops. If the carrier is generated more than a diffusion length away from the junction, then the collection probability of this carrier is quite low. Similarly, if the carrier is generated closer to a region such as a surface with higher recombination than the junction, then the carrier will recombine.

The generation rate is high at the surface and reduces exponentially with the cell depth.

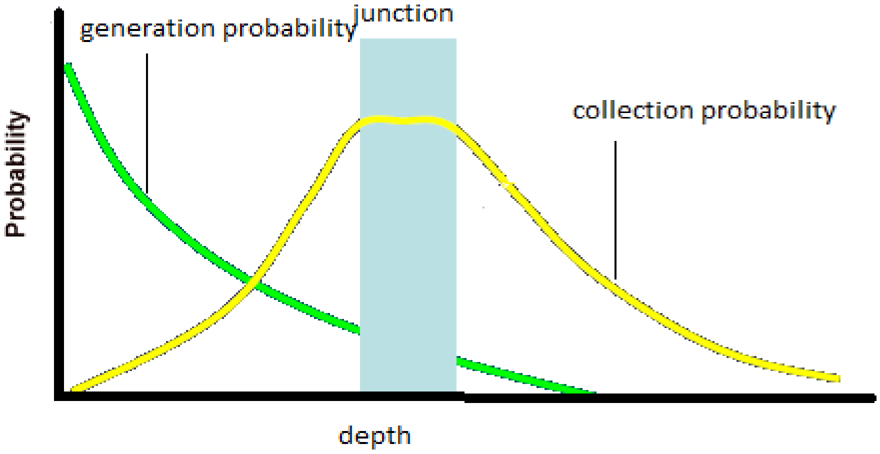

Figure 2.4 generation and collection probability Vs. depth of the cell

So, to increase the collection of light-generated carriers by the *p-n* junction, the junction need be kept closer to the top surface as the generation rate or generation probability of carriers is higher near the surface as shown in figure 2.4 above.

2.2.4 Drift-diffusion parameters

These parameters include mobility, lifetime and diffusion lengths for p-type and n-type silicon which controls the migration of the carriers in both the regions. The empirical formulas for hole mobility and lifetime obtained by *J. Del Alamo, S. Swirhim and R. Mswanson*, for electron mobility and lifetime obtained by *G. Masetti* and *S. Swirhim* respectively are used for calculating these parameters which are based on doping concentration and found reasonably accurate to be used in the modelling of silicon based solar cell [1], [2], [3].

$$\mu_n = 232 + \frac{1180}{1 + \left(\frac{Na}{8*10^{16}}\right)^{0.9}} \qquad \ldots 2.2$$

$$\mu_p = 130 + \frac{370}{1+ (\frac{N_d}{8*10^{16}})^{1.25}} \qquad \ldots 2.3$$

$$\tau_n = \frac{1}{3.45*10^{-12}N_a + 0.95*10^{-31}N_a^2} \qquad \ldots 2.4$$

$$\tau_p = \frac{1}{7.8*10^{-13}N_d + 1.7*10^{-31}N_d^2} \qquad \ldots 2.5$$

The diffusion coefficient and diffusion lengths of ‘p’ and ‘n’ type regions are related to the respective mobility and lifetimes as follow.

$$D_n = \mu_n \frac{kT}{q} \qquad \ldots 2.6$$

$$D_P = \mu_P \frac{kT}{q} \qquad \ldots 2.7$$

$$L_N = \sqrt{D_n \tau_n} \qquad \ldots 2.8$$

$$L_p = \sqrt{D_p \tau_p} \qquad \ldots 2.9$$

All the above formulas are dependent on doping concentrations and decreases with increase in doping concentration.

2.2.5 Surface recombination velocity

Any defects or impurities within or at the surface of the semiconductor promote recombination. The surface recombination rate is limited by the rate at which minority carriers move towards the surface. A parameter called the "surface recombination velocity", in units of cm/sec, is used to specify the recombination at a surface. In a surface with no recombination, the movement of carriers towards the surface is zero, and hence the surface recombination velocity is zero.

Typical the surface recombination velocity of bare n^+silicon is about 2x10^{5}cm/s [6] and for p^+ it is about 2x10^{5}cm/s. The surface recombination velocity can be reduced by surface passivation with suitable dielectric e.g. silicon nitride and also by highly doping the regions close to the surface with same dopant.

As low surface recombination velocity will improve the collection probability of the generated carriers. So a back surface field (i.e. p/p+ interface) is created which improves the collection probability as shown in figure 2.5.

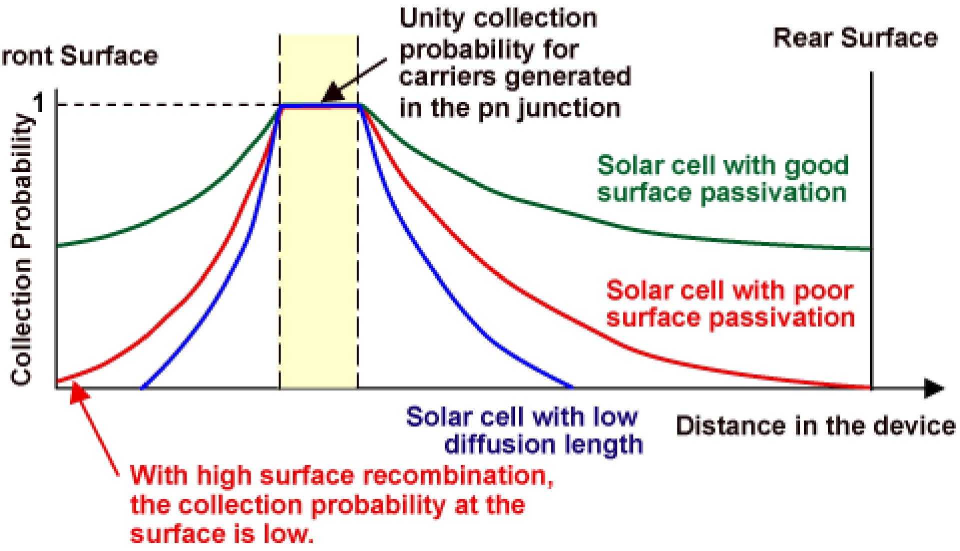

Figure 2.5 collection probability vs. depth of the cell

The p/p+ interface present a barrier to the electron that would have easily reached the ohmic contact and recombined there. The recombination velocity at the p/p+ interface (*the equation is derived by Hauser, is taken from the text book "SOLAR CELLS FROM BASICS TO ADVANCED SYSTEMS" by Chenming Hu)* can be expressed as

$$S_n = \frac{N_a}{N_a^+}\frac{D_n^+}{L_n^+}\coth\frac{W_p^+}{L_n^+} \qquad \ldots 2.10$$

Where, N_a^+, D_n^+, L_n^+ , and W_p^+ are the doping density, diffusion coefficient, diffusion length and thickness of p+ region respectively , N_a is the acceptor concentration.

From equation 2.10 if $W_p^+ = 0$, then $S_n = \infty$.
And if W_p^+ is comparable to L_n^+ and $N_a^+ >> N_a$ then $S_n \simeq 0$

2.2.6 Standard solar spectrums

The standard spectrum at the Earth's surface is called AM1.5G [4], (the G stands for global and includes both direct and diffuse radiation) or AM1.5D (which includes direct radiation only). The intensity of AM1.5D radiation can be approximated by reducing the AM0 spectrum by 28% (18% due to absorption and 10% to scattering). The global spectrum is 10% higher than the direct spectrum. These calculations give approximately 970 W/m^2 for AM1.5G. However, the standard AM1.5G spectrum has been normalized to give 1kW/m^2 due to the convenience of the round number and the fact that there are inherently variations in incident solar radiation.

The standard spectrum outside the Earth's atmosphere is called AM0, because at no stage does the light pass through the atmosphere. This spectrum is typically used to predict the expected performance of cells in space.

Since photovoltaic systems are spectrally selective, air mass spectra are a useful reference for assessing solar converter performance and charting performance improvements.

The photovoltaic industry, in association with research laboratories, predominantly uses the AM 1.5 as reference standard. This distribution of power as a function of wavelength (e. g. in $Wm-2\ nm-1$) provides a common reference for the evaluation of spectrally selective photovoltaic materials with various natural and artificial light sources. The conditions defining this spectrum are considered to be a reasonable average for the 48 contiguous states of the U.S.A over a period of one year. The AM 1.5 spectrum is defined for a cloudless sky (25 km visibility) with a 1.42 cm water vapour rural aerosol model; the data are available in the document, ASTM G-173-03.

AM 1.5 spectrum serve as reference for comparing efficiencies, but is not necessarily adequate for all solar converter designs. For active concentrators such as fluorescent solar collectors, capable of capturing diffuse light, corrections may be needed if they are used in regions (such as England) with cloudier skies [5]. Consequently, the norm ASTM G-173-03 defines two AM 1.5 spectra: global AM 1.5 which includes direct and diffuse light and the direct normal AM 1.5 which only considers direct light.

The integration of the global AM 1.5 spectrum over all wavelengths gives an irradiance of about967 $Wm-2$, which has been normalized to 1000 $Wm-2$ because of system design considerations (ISO9845-2: 1992 and ASTM E892-87: 1992).

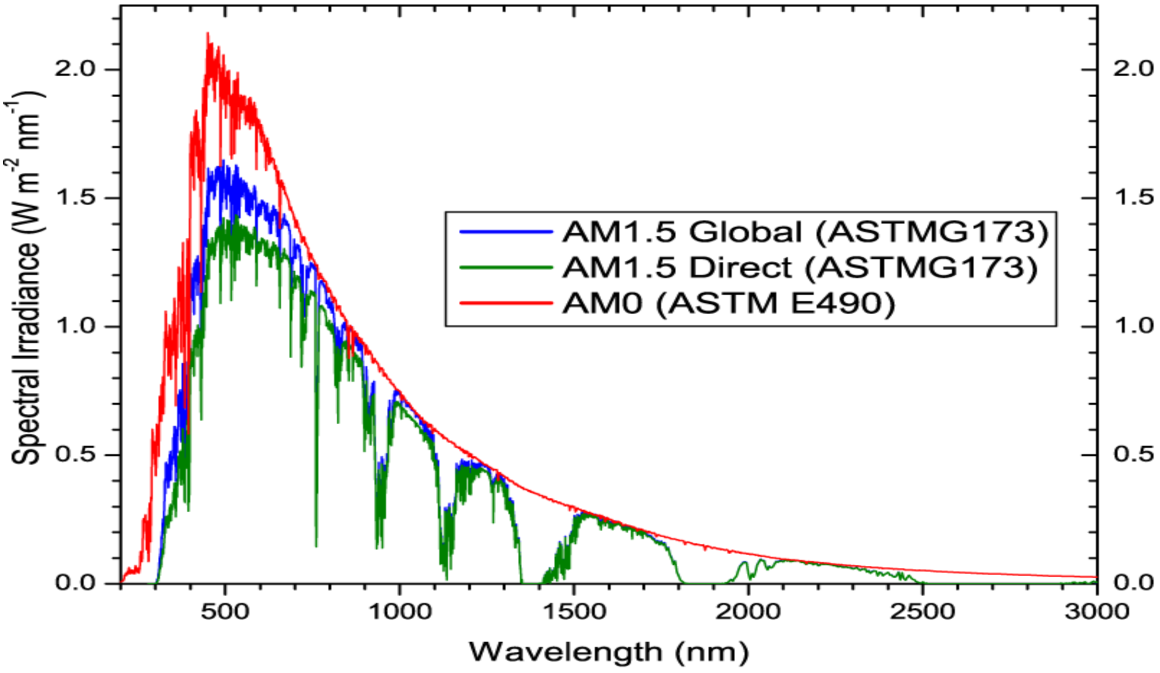

Figure 2.6 Standard Solar Spectra

So, we have used AM1.5 global in the modelling the single junction silicon solar cell. The AM1.5 global has the highest peak at 600nm approx.

2.3 IMPORTANT PARAMETERS AND RELATED EQUATIONS

This section explains all the important parameters which describe the photo-response of a solar cell and the corresponding equations used. It also explains the dependency of these parameters on others, such as doping, thicknesses of different regions etc. which affect the solar cell design.

2.3.1 Short circuit current density

When the solar cell is illuminated, a non-zero photocurrent is generated in the external electric short circuit with the sign indicated in figure2.7, provided that the emitter is an n-type semiconductor region and the base is a p-type layer. The simplified model which we will be using, assumes a solar cell of uniform doping concentrations in both the emitter and the base and p+ regions.

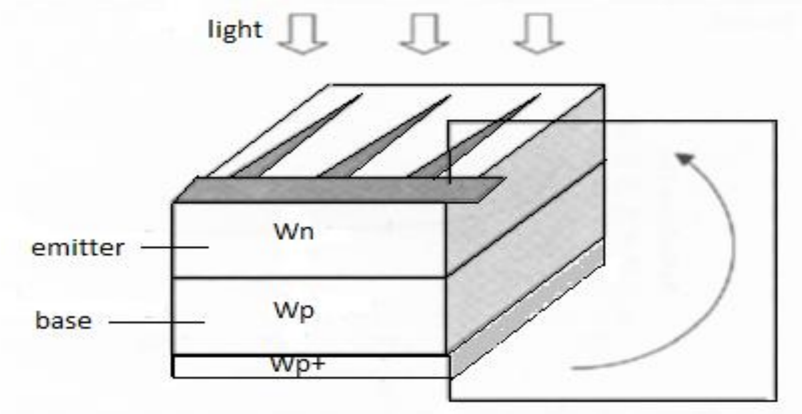

Figure 2.7 Schematic view of an externally short circuited solar cell

The above structure gives the value of the photocurrent collected by a $1cm^2$ surface solar cell, which is circulating in an external short circuit, when exposed to a monochromatic light. The short-circuit current is due to the generation and collection of light-generated carriers. The short-circuit current or the light-generated current is the largest current which may be drawn from the solar cell.

The short-circuit current depends on a number of factors which are described below:

1. **The area of the solar cell:** To remove the dependence of the solar cell area, it is more common to list the short-circuit current **density** (J_{sc} in A/cm^2) rather than the short-circuit current;
2. **The number of photons or photon flux**: it is the number of photons incident on the solar cell per unit surface per second. The spectral photon flux ϕ_0 received at the front surface of the emitter of a solar cell is related to the spectral irradiance and to the wavelength.

$$\phi_0 = 10^{16} \frac{I_\lambda * \lambda}{19.8} \quad [\frac{photons}{cm^2\ \mu m.S}] \qquad ...2.11$$

   Where, I_λ is the spectral irradiance written in W/$m^2\mu m$. Isc from a solar cell is directly dependant on the light intensity or the photon flux.
3. **The spectrum of the incident light:** For most solar cell measurement, the spectrum is standardised to the AM1.5G spectrum as described in the earlier section of 2.2.6
4. **The optical properties of silicon**: it includes absorption and reflection properties of the solar cell.
5. **The collection probability**: it depends chiefly on the surface passivation and the minority carrier lifetime in the base.

The photons incident on top surface of the cell gets absorbed in the three different regions i.e. emitter, base and depletion regions depending upon its wavelength and contribute to the corresponding current components, the expression for these current components (*taken from the text book "SOLAR CELLS FROM BASICS TO ADVANCED SYSTEMS" by Chenming Hu and Richard M. White)* are given as follows [7].

Emitter short circuit spectral density

$$J_{scP}(\lambda) = [\frac{q\phi_0(1-R(\lambda))\alpha(\lambda)L_p}{\alpha(\lambda)^2 L_P^2-1}]*$$

$$[\frac{\frac{S_pL_p}{D_p}+\alpha(\lambda)L_p-e^{-\alpha(\lambda)W_n}(\frac{S_pL_p}{D_p}\cosh\frac{W_n}{L_p}+\sinh\frac{W_n}{L_p})}{\frac{S_pL_p}{D_p}\sinh\frac{W_n}{L_p}+\cosh\frac{W_n}{L_p}} - L_p e^{-\alpha(\lambda)W_n}] \quad ...2.12$$

Base short circuit spectral current density

$$J_{scN}(\lambda) = [\frac{q\phi_0(1-R(\lambda))\alpha(\lambda)L_n}{\alpha(\lambda)^2 L_n^2-1}]*e^{-\alpha(\lambda)(W_n+W)}$$

$$*[\alpha(\lambda)L_n - \frac{\frac{S_nL_n}{D_n}\left(\cosh\frac{W_p}{L_n}-e^{-\alpha(\lambda)W_p}\right)+\sinh\frac{W_p}{L_n}+\alpha(\lambda)L_n e^{-\alpha(\lambda)W_p}}{\frac{S_nL_n}{D_n}\sinh\frac{W_p}{L_n}+\cosh\frac{W_p}{L_n}}] \quad ...2.13$$

The emitter and base short circuit currents densities are due to the diffusion of the carriers, which are generated due to the absorption of photons in emitter and base depending on the absorption coefficient at different wavelengths. If the carriers are generated within the depletion region, they are separated by the electric field. The electric field in the depletion region is so high that nearly all the light-generated carriers within the depletion region are swept out of the depletion region before they can recombine. The photocurrent due to the depletion region is therefore equal to the number of absorbed photons multiplied by q.

Depletion region short circuit spectral current density

$$J_{dr}(\lambda) = q\phi_0(1-R(\lambda))e^{-\alpha(\lambda)W_n}(1-e^{-\alpha(\lambda)W}) \quad ...2.14$$

Where, ϕ_0 is the spectral photon flux

$R(\lambda)$ is the reflectance of the cell surface.

$\alpha(\lambda)$ is the absorption coefficient.

L_n,D_n are the minority carrier diffusion length, diffusion coefficient in base region.

L_p,D_p are the minority carrier diffusion length, diffusion coefficient in emitter region.

S_p,S_n are the surface recombination velocities for emitter and base respectively.

W_n , W_p , W are the thicknesses of emitter, base and depletion region respectively.

The total short circuit current density is

$$J_{sc} = \int_0^{\infty} J_{sc\lambda} d\lambda = \int_0^{\infty} (J_{scP}(\lambda) + J_{scN}(\lambda) + J_{dr}(\lambda))\, d\lambda \qquad ...2.15$$

The units of the short-circuit current density are then A/cm^2. From equations 2.12, 2.13, 2.14 and 2.15 we can say that short circuit current of a single junction silicon solar cell can be modified or improved by

- Reducing $R(\lambda)$, this can be done by using ARC coating at the top surface of cell.
- Increasing$\alpha(\lambda)$, this can be done by increasing the optical length of the solar cell by means of texturing the front surface and using a reflector at the back.
- Satisfying the essential conditions (i.e. $L_p > W_n$ and $L_n > W_p$) which need be maintain always, as this condition will ensure the proper collection of minority carriers at the junction and hence a reasonable value of short circuit current can be achieved. Otherwise most of the minority carriers will recombine before being collected by the junction.

  To maintain these two conditions, one method is to keep the doping concentration of emitter and base regions of the cell low, but it will reduce the number of carriers in the semiconductor and thereby reduces the current. So it is not viable solution. Another method is to adjust both, the junction depth as well as doping concentrations to get a reasonable value of J_{sc}.
- Reducing S_p and S_n, this can be done by using a passivation layer at the surfaces and increasing the doping concentration of p+ region .

2.3.2 Quantum efficiency

The "quantum efficiency" (Q.E.) is the ratio of the number of carriers collected by the solar cell to the number of photons of a given energy incident on the solar cell. The quantum efficiency may be given either as a function of wavelength or as energy. If all photons of a certain wavelength are absorbed and the resulting minority carriers are collected, then the quantum efficiency at that particular wavelength is unity. The quantum efficiency for photons with energy below the band gap is zero.

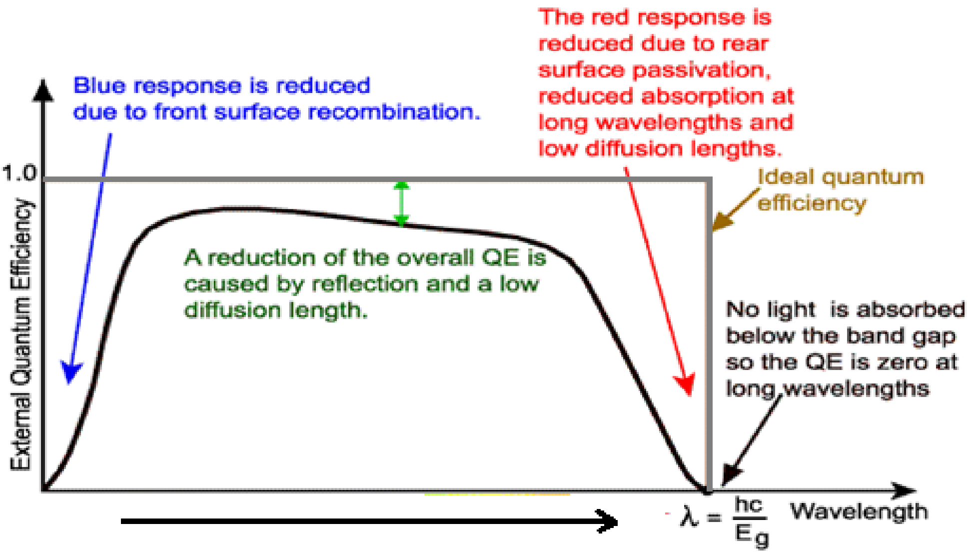

Figure 2.8 The quantum efficiency of a silicon solar cell

While quantum efficiency ideally has the square shape shown above, the quantum efficiency for most solar cells is reduced due to recombination effects. For example, front surface passivation affects carriers generated near the surface, and since blue light is absorbed very close to the surface, high front surface recombination will affect the "blue" portion of the quantum efficiency. Similarly, green light is absorbed in the bulk of a solar cell and a low diffusion length will affect the collection probability from the solar cell bulk and reduce the quantum efficiency in the green portion of the spectrum. The QE is given by

$$QE = \frac{J_{sc\lambda}}{q\phi_0(1-R(\lambda))} \quad ...2.16$$

From equations 2.12, 2.13, 2.14 and 2.15, 2.16 we can say that QE can be improved by

- Increasing$\alpha(\lambda)$, this can be done by increasing the optical length of the solar cell by means of texturing the front surface and using a reflector at the back.
- Reducing S_p and S_n, this can be done by using a passivation layer at the surfaces and increasing the doping concentration of p+ region.
- Satisfying the essential conditions (i.e. $L_p > W_n$ and $L_n > W_p$) which need be maintain always, as this condition will ensure the proper collection of minority carriers at the junction and hence a reasonable value of short circuit current can be achieved. Otherwise most of the minority carriers will recombine before being collected by the junction.

  To maintain these two conditions, we need to adjust both, the junction depth as well as doping concentrations to get a reasonable value of J_{sc} and hence QE.

2.3.3 Spectral response

The spectral response is conceptually similar to the quantum efficiency. The quantum efficiency gives the number of electrons output by the solar cell compared to the number of photons incident on the device, while the spectral response is the ratio of the current generated by the solar cell to the power incident on the solar cell. A spectral response curve is shown below.

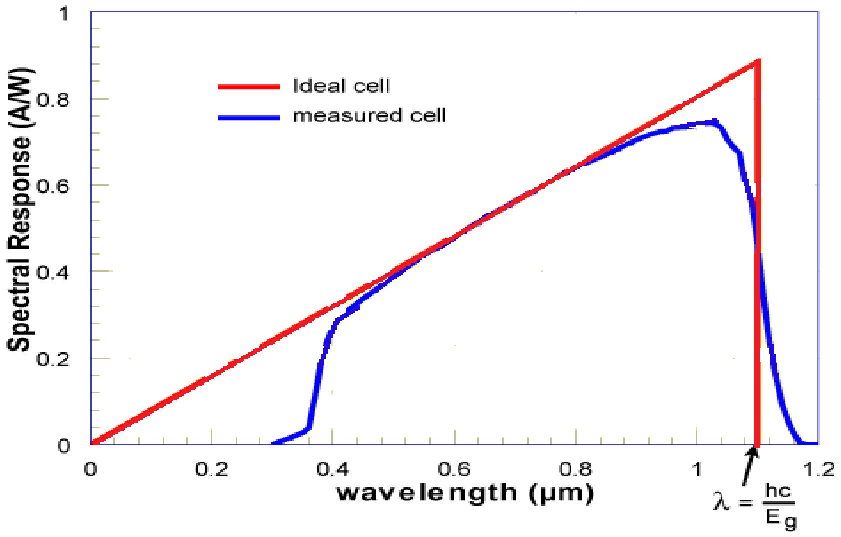

Figure 2.9 The spectral response of a silicon solar cell

The ideal spectral response is limited at long wavelengths by the inability of the semiconductor to absorb photons with energies below the band gap. This limit is the same as that encountered in quantum efficiency curves. However, unlike the square shape of QE curves, the spectral response decreases at small photon wavelengths. At these wavelengths, each photon has a large energy, and hence the ratio of photons to power is reduced. Any energy above the band gap energy is not utilised by the solar cell and instead goes to heating the solar cell. The inability to fully utilize the incident energy at high energies and the inability to absorb low energies of light represents a significant power loss in solar cells consisting of a single *p-n* junction. Spectral response is given by

$$\mathrm{SR} = \frac{q\lambda}{hc}\,\mathrm{QE} = \frac{J_{sc\lambda}}{I_{\lambda}(1-R(\lambda))} \qquad ...2.17$$

From equations 2.12, 2.13, 2.14 and 2.15, 2.17 we can say that SR can be improved by

- Increasing $\alpha(\lambda)$, this can be done by increasing the optical length of the solar cell by means of texturing the front surface and using a reflector at the back.
- Reducing S_p and S_n , this can be done by using a passivation layer at the surfaces and increasing the doping concentration of p+ region.
- Satisfying the essential conditions (i.e. $L_p > W_n$ and $L_n > W_p$) which need be maintain always, as this condition will ensure the proper collection of minority carriers at the junction and hence a reasonable value of short circuit current can be achieved. Otherwise most of the minority carriers will recombine before being collected by the junction.

To maintain these two conditions, we need to adjust both, the junction depth as well as doping concentrations to get a reasonable value of J_{sc} and hence SR.

2.3.4 Dark current density

Applying voltage to p-n junction, semiconductor allows an increase in rate at which majority carrier diffuse across the junction and become minority carrier. Holes that diffuse from ‘p’ region to ‘n’ region are called injected minority carrier holes in ‘n’ region, while for electron that diffuse from n region to ‘p’ region are injected minority carrier electrons in ‘p’ region. So the saturation current density of holes and electrons at edge of depletion region (*the equations are taken from the text book “SOLAR CELLS FROM BASICS TO ADVANCED SYSTEMS” by Chenming Hu and Richard M. White)* is given by [7]

$$J_{0p} = q\,\frac{D_p n_i^2}{L_p N_d}\,\frac{\frac{S_p L_p}{D_p}\cosh\frac{W_n}{L_p} + \sinh\frac{W_n}{L_p}}{\frac{S_p L_p}{D_p}\sinh\frac{W_n}{L_p} + \cosh\frac{W_n}{L_p}} \qquad ...2.18$$

or,
$$J_{0p} = q\frac{D_p p_n}{L_p}\frac{\frac{S_p L_p}{D_p}cosh\frac{W_n}{L_p} + sinh\frac{W_n}{L_p}}{\frac{S_p L_p}{D_p}sinh\frac{W_n}{L_p} + cosh\frac{W_n}{L_p}} \quad ...2.19$$

$$J_{0n} = q\frac{D_n n_i^2}{L_n N_a}\frac{\frac{S_n L_n}{D_n}cosh\frac{W_p}{L_n} + sinh\frac{W_p}{L_n}}{\frac{S_n L_n}{D_n}sinh\frac{W_p}{L_n} + cosh\frac{W_p}{L_n}} \quad ...2.20$$

or,
$$J_{0n} = q\frac{D_p n_p}{L_p}\frac{\frac{S_p L_p}{D_p}cosh\frac{W_n}{L_p} + sinh\frac{W_n}{L_p}}{\frac{S_p L_p}{D_p}sinh\frac{W_n}{L_p} + cosh\frac{W_n}{L_p}} \quad ...2.21$$

$$J_0 = J_{0p} + J_{0n} \quad ...2.22$$

$$J = J_0(e^{-\frac{v}{V_t}} - 1) \quad ...2.23$$

Where, v is voltage across the diode terminals, p_n and n_p in equations 2.19 and 2.21 respectively are the minority carrier concentrations in their respective regions.

The dark current density depends on J_0 i.e. the reverse saturation current of the junction. It is desirable to minimize the reverse saturation current J_0 so that the dark current will reduce and hence the net current of single junction silicon solar cell increases. So from equations 2.18, 2.19, 2.20, 2.21, 2.22, 2.23 it can be observed that the reverse saturation current of the junction can be reduce by

- High doping reduces the minority carrier concentrations in the cell as $J_{0p} \propto p_n$ and $J_{0n} \propto n_p$ as shown in equations 2.19 and 2.21 respectively.
- Reducing S_p and S_n, this can be done by using a passivation layer at the surfaces and increasing the doping concentration of p+ region.

2.3.5 Open circuit voltage

The open-circuit voltage, V_{OC}, is the maximum voltage available from a solar cell [7], and this occurs at zero current (*the equations are taken from the text book "SOLAR CELLS FROM BASICS TO ADVANCED SYSTEMS" by Chenming Hu and Richard M. White)* and is given by

$$V_{OC} = \frac{kT}{q}\ln\left(\frac{J_{sc}}{J_0} + 1\right) \quad ...2.24$$

The above equation shows that V_{oc} depends on the saturation current density of the solar cell and the light-generated current density. While J_0 depends on recombination in the solar cell which needs to be minimised to reduce J_0 and hence improve V_{oc}. Open-circuit voltage is then a measure of the amount of recombination in the device. Silicon solar cells on high quality single crystalline material have open-circuit voltages of up to 730 mV under one sun and AM1.5 condition.

From the equation 2.24 it is observed that V_{oc} is depends logarithmically on the $\frac{J_{sc}}{J_0}$ ratio this means that

- The value of the open circuit voltage scales logarithmically with the short circuit current density as well as reverse saturation current density. While J_{sc} typically has a small variation, the key effect is the saturation current density, since this may vary by orders of magnitude. The saturation current density, J_0 depends on doping concentration of the solar cell.
- Open circuit voltage is independent of the cell area.

2.3.6 Fill factor

The short-circuit current and the open-circuit voltage are the maximum current and voltage respectively from a solar cell. However, at both of these operating points, the power from the solar cell is zero. The "fill factor", more commonly known by its abbreviation "FF", is a parameter which, in conjunction with V_{oc} and I_{sc}, determines the maximum power from a solar cell [7]. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc}. Graphically, the FF is a measure of the "squareness" of the solar cell and is also the area of the largest rectangle which will fit in the IV curve. The FF is illustrated below.

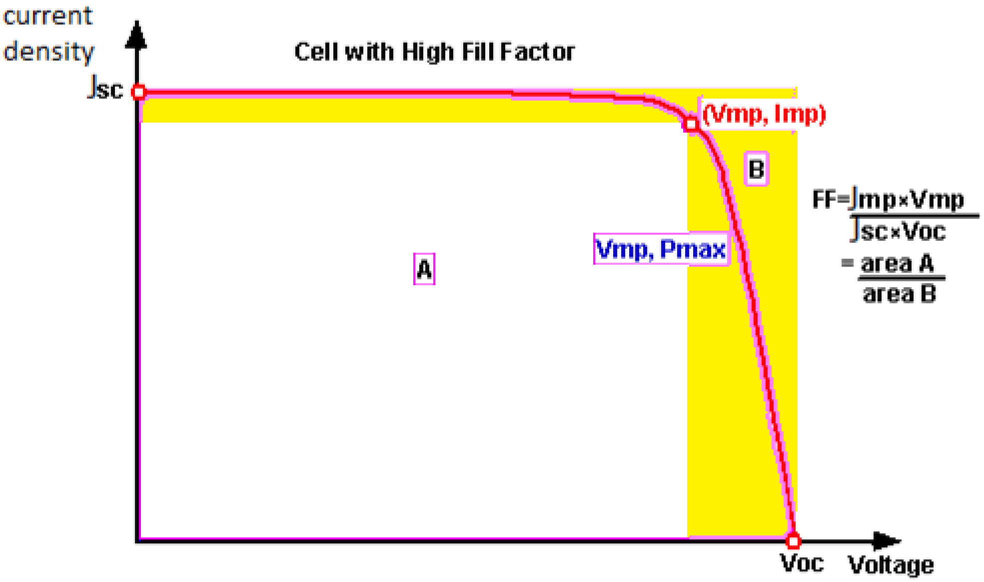

Figure 2.10 Graph of cell output current as function of voltage

$$FF = \frac{J_{mp}V_{mp}}{J_{sc}V_{oc}} \qquad ...2.25$$

In the case of ideal solar cell fill-factor is a function of open circuit parameters (*the equation is taken from the text book "SOLAR CELLS OPERATING PRINCIPLES, TECHNOLOGY, AND SYSTEM APPLICATIONS" by Martin A. Green)* and can be calculated as follows [8]:

$$FF = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1} \qquad ...2.26$$

Where,

$$v_{oc} = V_{oc}\frac{q}{kT} \qquad ...2.27$$

The fill factor will depend mainly on $\mathrm{V_{oc}}$ in addition to that it also depends on the resistive losses, which will be discussed in the later sections.

2.3.7 Efficiency

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight. Therefore, conditions under which efficiency is measured must be carefully controlled in order to compare the performance of one device to another.

The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity (*the equations are taken from the text book "SOLAR CELLS FROM BASICS TO ADVANCED SYSTEMS" by Chenming Hu and Richard M. White)* and is defined as [7]:

$$P_{MAX} = V_{OC}I_{SC}FF \qquad ...2.28$$

$$\eta = \frac{V_{OC}I_{SC}FF}{P_{in}} \qquad ...2.29$$

Equation 2.29 shows that efficiency depends on Voc, Isc and FF, which can be improved by enhancing the reflectance of light, recombination losses, collection of the generated carriers. Efficiency also depends on resistive losses.

2.4 A METHOD TO ENHANCE THE EFFICIENCY

In designing single junction solar cells, the principles for maximising cell efficiency are:

2.4.1 Increasing the amount of light entering into the cell and reducing the amount of light leaking away from the cell by using anti-reflective coating, texturing.

1. Anti-reflective coating

Anti-reflection coatings on solar cells are similar to those used on other optical equipment such as camera lenses. They consist of a thin layer of dielectric material, with a specially chosen thickness so that interference effects in the coating cause the wave reflected from the anti-reflection coating top surface to be out of phase with the wave reflected from the semiconductor surfaces. These out-of-phase reflected waves destructively interfere with one another, resulting in zero net reflected energy.

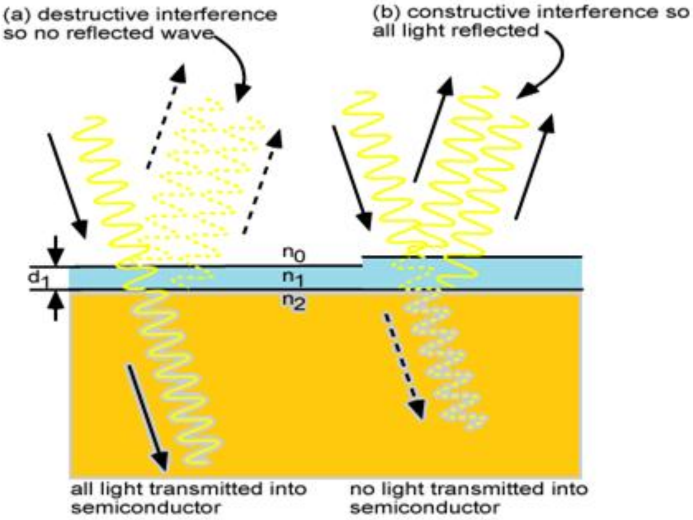

Figure 2.11 constructive and destructive interference due to ARC

The thickness of the anti-reflection coating is chosen so that the wavelength in the dielectric material is one quarter the wavelength of the incoming wave. For a quarter wavelength anti-reflection coating of a transparent material with a refractive index n_1 and light incident on the coating with a free-space wavelength λ_0, the thickness d_1 which causes minimum reflection is calculated by [7] (*the equations are taken from the text book "SOLAR CELLS FROM BASICS TO ADVANCED SYSTEMS" by Chenming Hu and Richard M. White)*:

$$d_1 = \frac{\lambda_0}{4n_1} \qquad ...2.30$$

Reflection is further minimised if the refractive index of the anti-reflection coating is the geometric mean of that of the materials on either side; that is, glass or air and the semiconductor. This is expressed by:

$$n_1 = \sqrt{n_0 n_2} \qquad ...2.31$$

$$R = \frac{r_1^2 + r_2^2 + 2r_1 r_2 \cos 2\theta}{1 + r_1^2 r_2^2 + 2r_1 r_2 \cos 2\theta} \qquad \text{...2.32}$$

Where,

$$r_1 = \frac{n_0 - n_1}{n_0 + n_1}, r_2 = \frac{n_1 - n_2}{n_1 + n_2} \text{ and } \theta = \frac{2\pi n_1 d_1}{\lambda}$$

While the reflection for a given thickness, index of refraction, and wavelength can be reduced to zero using the equations above, the index of refraction is dependent on wavelength and so zero reflection occurs only at a single wavelength. For photovoltaic applications, the refractive index, and thickness are chosen in order to minimise reflection for a wavelength of 0.6 µm. This wavelength is chosen since it is close to the peak power of the solar spectrum.

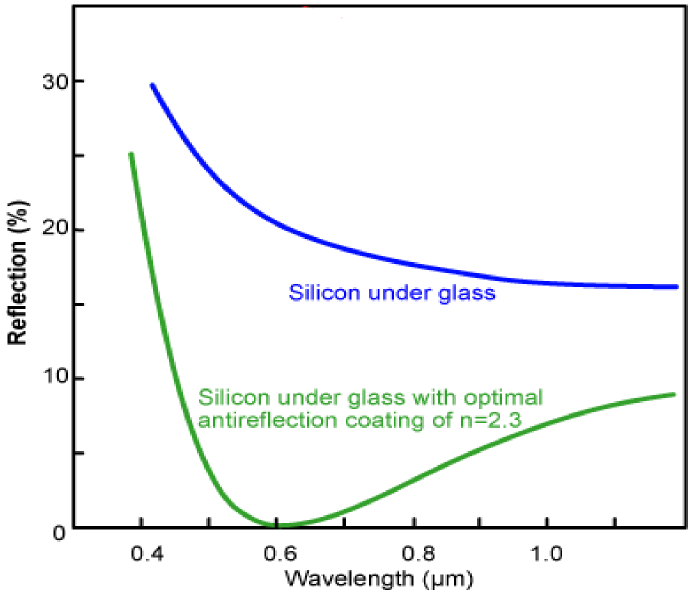

Figure 2.12 reflection of light from silicon surface with and without ARC

2. Texturing

Surface texturing, in combination with an anti-reflection coating be used to minimise reflection. Any "roughening" of the surface reduces reflection by increasing the chances of reflected light bouncing back onto the surface, rather than out to the surrounding air.

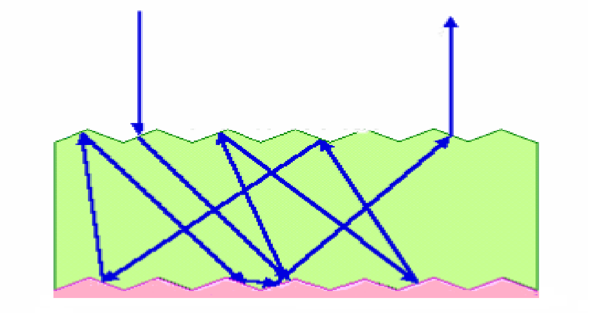

Figure 2.13 Texturing of silicon surface

High efficiency in a solar cell is achieved by maximizing light-generated current and minimizing losses in the bulk base and emitter, within the collecting junction and the surfaces. Texturization of the front surface has been successfully employed to improve the short-circuit current for crystalline silicon solar cells [9] through the absorption of light effectively closer to the junction, reduction of front surface reflection losses by multiple incidence, and the trapping of weakly absorbed photon within the cell.

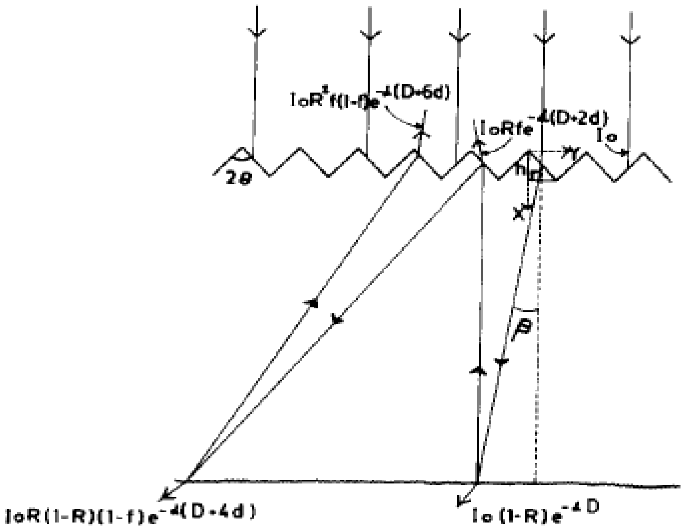

Figure 2.14 Light trapping by Lambertian rear surface through pyramidal top surface.

Texturing improves the effective absorption coefficient α^* of silicon which in turn improves the short circuit current of the solar cell as the absorption of photons increases. The expressions are derived by Hiranmay Saha, Swapan K. Datta, Kanak Mukhopadhyay, S. Banerjee,and Manish K. Mukherjee, and is given as

$$\alpha^* = \frac{\alpha}{\cos\beta} + \frac{1}{d}\ln[\frac{1-R(1-f)e^{-4\alpha d}}{1-R((1-fe^{-2\alpha d})}] \qquad \text{...2.33}$$

Where, α is the absorption coefficient of silicon explained above in section 2.2.1, β is determined by Snell's law and is given by

$$\beta = cos^{-1}\left(\frac{cos\theta}{\mu}\right) - \theta \qquad \text{...2.34}$$

is a function of wavelength of light through the dependence of the µ on wavelength, d is the cell thickness, D is the path length, R is reflectivity of the lambertian reflector. θ is the half of the face angle ($2\theta = 70.53^0$ [9]). considered for simulation) f is the fraction of light being leaked out of the front surface at each impact and is given by ($f = \frac{1}{\mu^2}$) , µ being the refractive index of the cell material.

2.5 Series and shunt resistance

The series and shunt resistance will affect mainly fill factor and hence efficiency, as we can see in figures 2.18 and 2.20 below the resistive losses will reduces the maximum power that a cell can deliver to the load.

2.5.1 Series resistance

Series resistance in a solar cell has three causes: firstly, the movement of current through the emitter and base of the solar cell; secondly, the contact resistance between the metal contact and the silicon; and finally the resistance of the top and rear metal contacts. The main impact of series resistance is to reduce the fill factor and hence efficiency, although excessively high values may also reduce the short-circuit current.

The series resistance of the cell is modelled by L.J. Caballero, A. Martinez, P. Sanchez-Friera, M. A. Vazquez, J. Alonso as shown in figure below [10].

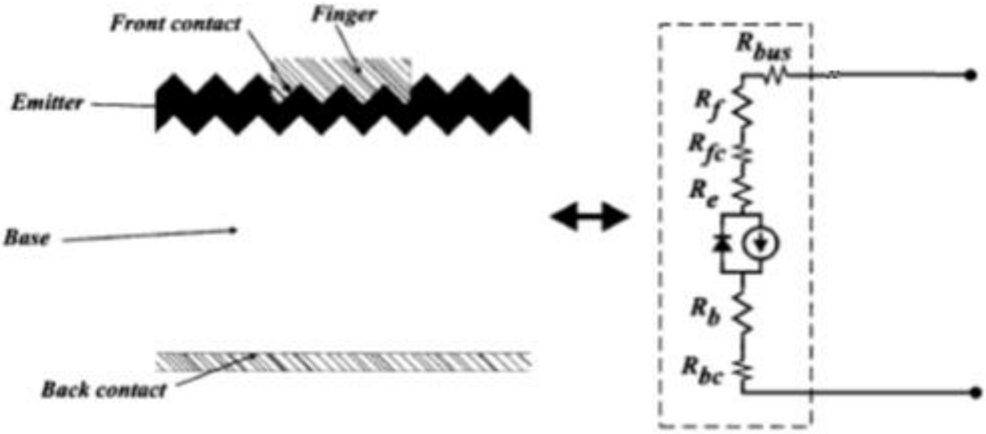

Figure 2.15 Components of the cell's series resistance

Component	Expression
Emitter	$R_e = \frac{n.S^2}{3L} \frac{R_e}{(L/_2 - W_{bus})}$
Base	$R_b = \rho_{base} \frac{8n.W_p}{L^2} + \rho^{+}_{base} \frac{8n.W_p^{+}}{L^2}$
Metallic finger	$R_f = \frac{n.s}{3L} \frac{\rho_{metal}}{W_f h_f} (L/_2 - W_{bus})$
Bus bar	$R_{bus} = \frac{\rho_{metal}}{3n} \frac{L}{W_{bus} h_{bus}}$
Rear contact resistance	$R_{fc} = \frac{8n.s.\rho_c}{L(W_f.L + 2W_{bus}.(s - W_f))}$
Front contact resistance	$R_{bc} = \frac{8n.\rho_c}{L^2}$

Table 2.1 Analytical expressions of the series resistance components for a two bus-bar cell

Where, ρ_{base} is the resistivity of the p layer, ρ_{base}^{+} is the resistivity of the p+ layer, ρ_{metal}, ρ_c are the resistivity of the metallic grid and semiconductor- metal contact specific resistivity respectively. R_e is emitter layer sheet resistance, L is wafer side length, W_p is the base width, W_p^{+} is the p+ region width, W_{bus} , W_f are widths of busbar and fingers respectively, 'S' is the separation between the fingers, n is the number bonding points per busbar.

The total series resistance is given by,

$$R_S = \frac{\sum R_{components}}{8n} \qquad \text{...2.35}$$

For a silicon cell [11], ρ_c < 2E-3 ohm-cm^2,
For the n-contact Nd> 10^{19} cm^{-3}.
For the p-contact Na> 10^{17} cm^{-3}

So we have assumed ρ_c = 1E-3 ohm-cm^2, and a metallic grid structure of silver with a resistivity of 1.59E-6 ohm-cm, its dimensions are as follows.

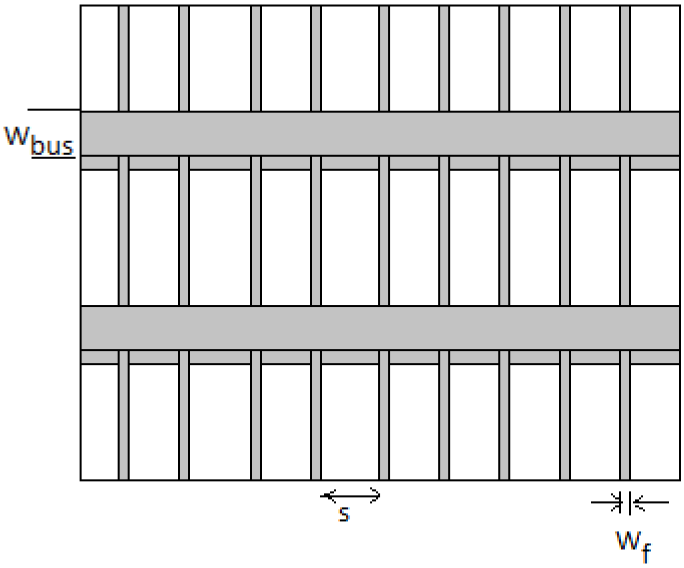

Figure 2.16 metallic grid structure

- Spacing between the metal fingers (S) = 520 um.
- Width of the fingers (W_f) = 6 um.
- Width of the busbars (W_{bus}) = 100 um.
- Aspect ratio=0.2
- n=20.

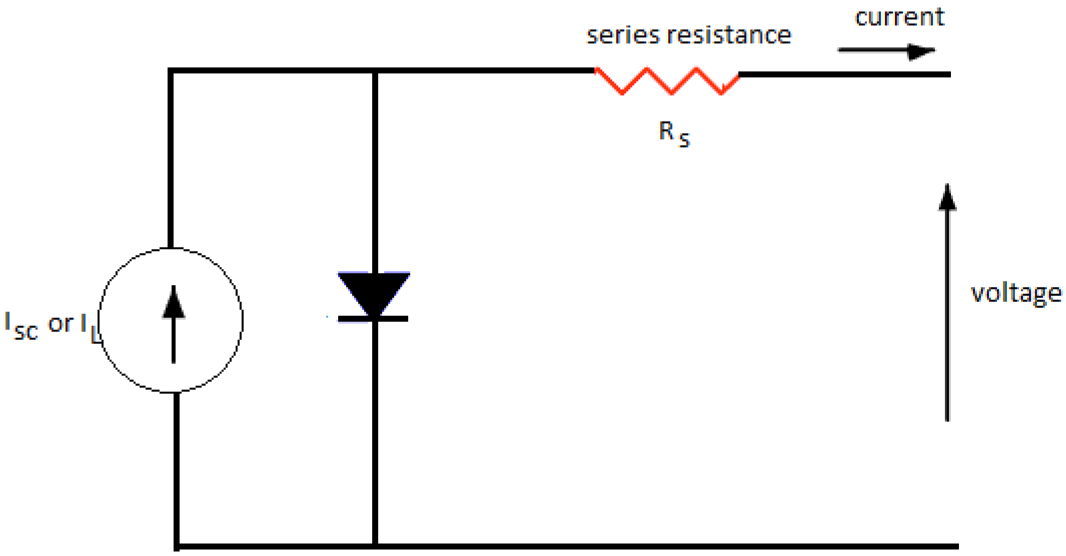

Figure 2.17 Schematic of a solar cell with series resistance

$$I = I_L - I_0(e^{[\frac{q(v+IR_S)}{kT}]} -1) \qquad ...2.36$$

Where, I is the cell output current, I_L is the light generated current, V is the voltage across the cell terminals, T is the temperature, q and k are constants, and R_S is the cell series resistance.

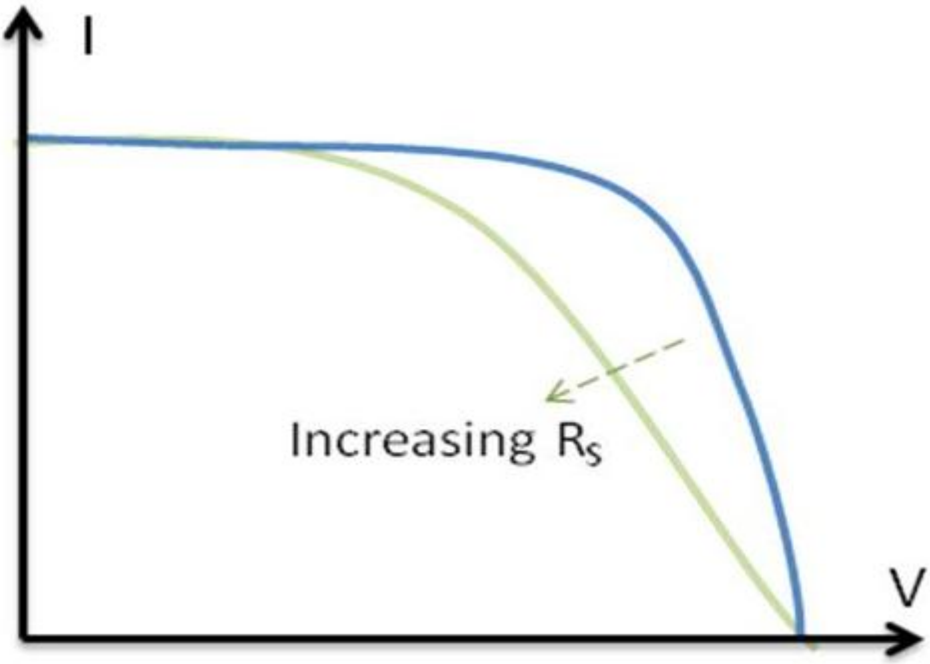

Figure 2.18 IV characteristic of solar cell with increasing series resistance of cell

2.5.2 Shunt resistance

Power losses caused by the presence of a shunt resistance, R_{SH}, are typically due to manufacturing defects, rather than poor solar cell design. Low shunt resistance causes power losses in solar cells by providing an alternate current path for the light-generated current. Such a diversion reduces the amount of current flowing through the solar cell junction and reduces the voltage from the solar cell. The effect of a shunt resistance is particularly severe at low light levels, since there will be less light-generated current. The loss of this current to the shunt therefore has a larger impact. In addition, at lower voltages where the effective resistance of the solar cell is high, the impact of a resistance in parallel is large.

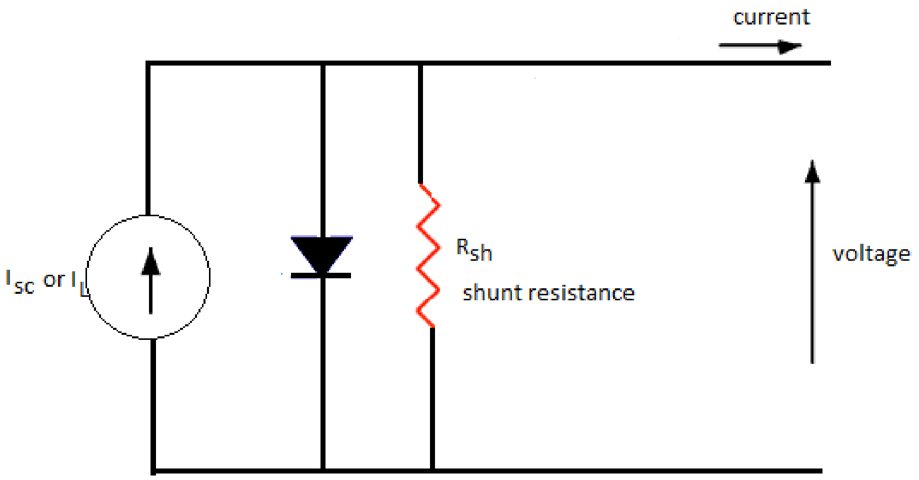

Figure 2.19 Schematic of a solar cell with shunt resistance

$$I = I_L - I_0(e^{\left[\frac{qv}{kT}\right]} - 1) - \frac{v}{R_{sH}} \qquad \text{...2.37}$$

Where, I is the cell output current, I_L is the light generated current, V is the voltage across the cell terminals, T is the temperature, q and k are constants, and R_{SH} is the cell series resistance.

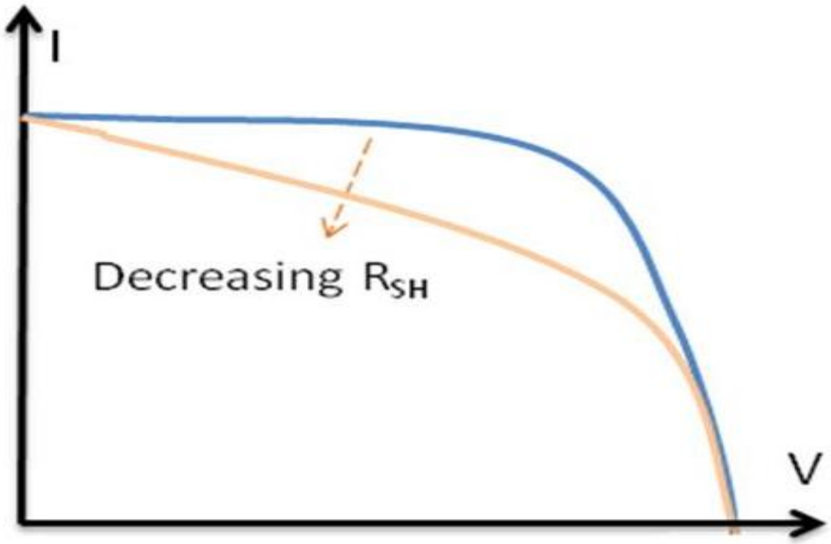

Figure 2.20 IV characteristic of solar cell with decreasing shunt resistance of cell

In this thesis R_{SH} is considered to be infinite.

2.5.3 Minimizing the resistive losses.

The resistive losses in cell the will greatly affect its efficiency especially series resistance. So, to minimise the series resistance we need to increase the doping. But increase in the will reduces the diffusion length of the minority carrier to nullify this effect the junction should to be kept closer to the surface so that emitter could be heavily doped to minimise the series resistance of the emitter but the limiting factor here is the lateral of the emitter which increases as the junction is closer to the surface so that need to be balanced.

Now as the junction is closer to the top surface, the base diffusion length need to be increased so that the carriers generated in the base can be collected efficiently, this can be done by reducing the base doping but reducing the doping will increase the series resistance, so that need be balanced again.

To decrease the series resistance further p+ region thickness can be increased which will decreases the base resistance further.

2.6 Schematic of solar cell model

In this thesis R_{SH} is considered to be infinite. While the recombination at the space charge region of solar cells explains non-ohmic current paths in parallel with the basic solar cell. This is relevant at low voltage bias and can be represented in an equivalent circuit by a second diode term with a saturation current I_{02} which is derived by C.T. SAH, is different from the saturation current density of the ideal solar cell diode [12] and is given by,

$$I = I_{02}(e^{\frac{q(v+IR_S)}{2kT}} - 1) \qquad \text{...2.38}$$

And is given by,

$$I_{02} = \frac{qAn_i\pi}{2\sqrt{\tau_n\tau_p}}\frac{kT}{q\xi_{max}} \qquad \text{...2.39}$$

Where, A is the area of the top surface of the cell, and ξ_{max} is the maximum electric field strength in the junction. Its value is given by,

$$\xi_{max} = -\,[\frac{2q}{\varepsilon}\ (V_{oc} - v)/(\frac{1}{N_a} - \frac{1}{N_d})]^{0.5} \qquad \text{...2.40}$$

Now, the overall I-V equation is

$$I = I_L - I_0(e^{[\frac{q(v+IR_S)}{kT}]}\text{-}1) - I_{02}(e^{[\frac{q(v+IR_S)}{kT}]}) \qquad \text{...2.41}$$

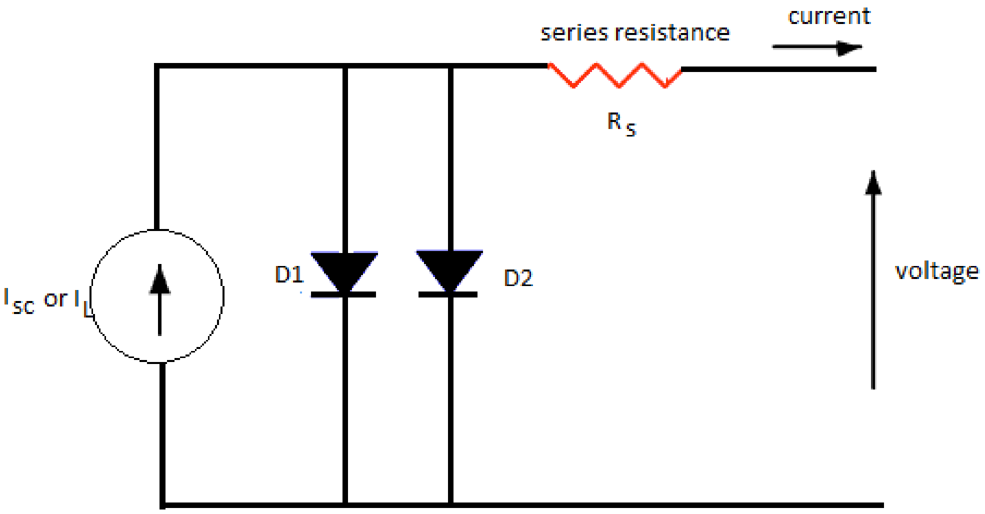

Figure 2.21 solar cell model as a circuit

From all the above sections discussed in this chapter, it can be concluded that to design an optimum solar cell structure with better efficiency one needs to vary three parameters essentially i.e. doping concentrations, junction depth and thickness of the cell but to reduce the resistive losses further we need to vary another parameter i.e. p+ region thickness (keeping *cell thickness constant*).

Chapter 3

IMPLEMENTATION OF THE SOLAR CELL MODELLING IN MATLAB

This chapter deals with the detailed discussion on the how the various equations, which are already discussed in the previous chapter, are linked with each other and the code is written in the MATLAB to analyse the various parameters e.g. Jsc, Voc etc. of the single junction silicon solar cell and hence an optimised cell structure with higher efficiency is archived. The code is divided into three modules so that coding would be easier and can be understood comprehensively. The first module is to study the effect of variation in doping and junction depth on the cell performance. The next module will include the ARC coating and the texturing models into the code whereas the last module includes the resistive effects of the cell. It also includes the effects of variation in p+ region thickness and the overall cell thickness to get an optimum cell structure of maximum efficiency.

3.1 MODULE 1: Doping concentration and junction depth.

This module deals with the dependence of solar cell parameters such as short circuit current density, open circuit voltage etc. on doping concentration and junction depth. For generating this module an initial structure (as shown in figure 3.1 below) of 400 um cell thickness with an emitter thickness of 0.1µm is considered.

Cross-sectional area is $1cm^2$.
Acceptor concentration (Na) = $1E15cm^{-3}$
Donor concentration (Nd) = $1E15cm^{-3}$
P+ concentration (Na+) = $1E19cm^{-3}$

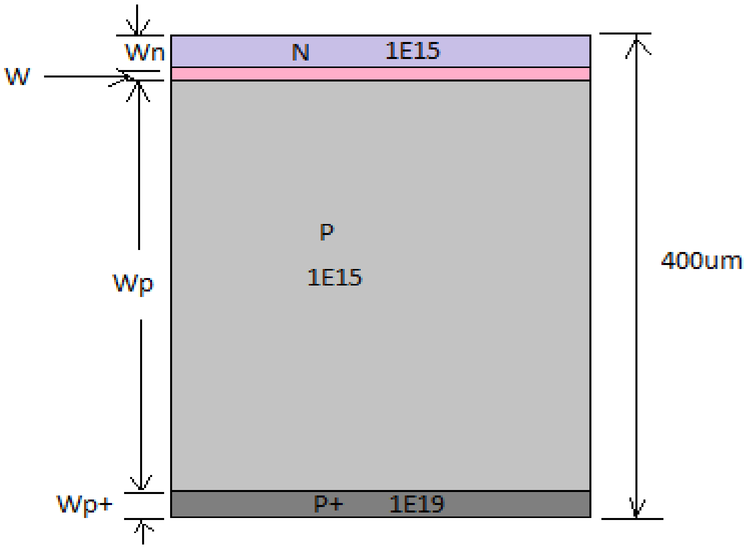

Figure 3.1 p-n junction silicon solar cell

Along with the initial structure, the following inputs are given to the code as a text file.

- Wavelength (nm) from 290 nm-1200 nm.
- Absorption coefficient of silicon (cm^{-1}) for different wavelengths in steps of 10 nm.
- Reflectance of silicon surface for different wavelengths in steps of 10 nm.
- Solar irradiance value of AM1.5G [4] in $\mathrm{Watt}/_{\mathrm{m}^2 - \mathrm{um}}$ for different wavelengths in steps of 10 nm.

The values of all the above parameters are given in APPENDIX-A. In addition to all the above input parameters the surface recombination velocity of front and back surface of bare silicon is considered as $2\text{x}10^{5}$ cm/s [6]. The recombination velocity at p/p+ interface is calculated by the equation given below, as already been discussed in chapter 2.

$$S_n = \frac{N_a}{N_a^+}\frac{D_n^+}{L_n^+}\coth\frac{W_p^+}{L_n^+} \qquad \text{...3.1}$$

Where, N_a^+, D_n^+, L_n^+ , and W_p^+ are the doping density, diffusion coefficient, diffusion length and thickness of p+ region respectively , $\mathrm{N_a}$ is the acceptor concentration.

Initially, using solar irradiance values, the number of photons incident on the solar cell surface is determined for each wavelength using the equation shown below, as already been discussed in chapter 2.

$$\phi_0 = 10^{16}\,\frac{I_\lambda * \lambda}{19.8} \quad [\frac{photons}{cm^2\ \mu m.S}] \qquad \text{...3.2}$$

Where, I_λ is the spectral irradiance written in W/m^2µm. Isc from a solar cell is directly dependant on the light intensity or the photon flux.

In addition to the photon flux determined above, the values of absorption coefficient, Reflectance are used in the equations shown below, as already been discussed in chapter 2.

Emitter short circuit spectral density

$$J_{scP}(\lambda) = [\frac{q\phi_0\big(1-R(\lambda)\big)\alpha(\lambda)L_p}{\alpha(\lambda)^2L_P^2-1}]*$$

$$[\frac{\frac{S_pL_p}{D_p}+\alpha(\lambda)L_p-e^{-\alpha(\lambda)W_n}(\frac{S_pL_p}{D_p}\,cosh\frac{W_n}{L_p}+sinh\frac{W_n}{L_p})}{\frac{S_pL_p}{D_p}sinh\frac{W_n}{L_p}+cosh\frac{W_n}{L_p}} - L_pe^{-\alpha(\lambda)W_n}] \qquad \text{...3.3}$$

Base short circuit spectral current density

$$J_{scN}(\lambda) = [\frac{q\phi_0(1-R(\lambda))\alpha(\lambda)L_n}{\alpha(\lambda)^2L_n^2-1}]*e^{-\alpha(\lambda)(W_n+W)}$$

$$*\ [\alpha(\lambda)L_n - \frac{\frac{S_nL_n}{D_n}\left(cosh\frac{W_p}{L_n} - e^{-\alpha(\lambda)W_p}\right)+ sinh\frac{W_p}{L_n} + \alpha(\lambda)L_n\, e^{-\alpha(\lambda)W_p}}{\frac{S_nL_n}{D_n}sinh\frac{W_p}{L_n}+ cosh\frac{W_p}{L_n}}] \qquad ...3.4$$

Depletion region short circuit spectral current density

$$J_{dr}(\lambda) = q\phi_0(1 - R(\lambda))e^{-\alpha(\lambda)W_n}(1 - e^{-\alpha(\lambda)W}) \qquad ...3.5$$

Where, ϕ_0 *is the spectral photon flux*
$R(\lambda)$ *is the reflectance of the cell surface.*
$\alpha(\lambda)$ *is the absorption coefficient.*
L_n,D_n *are the minority carrier diffusion length, diffusion coefficient in base region.*
L_p,D_p *are the minority carrier diffusion length, diffusion coefficient in emitter region.*
S_p,S_n *are the surface recombination velocities for emitter and base respectively.*
W_n , W_p , *W are the thicknesses of emitter, base and depletion region respectively.*

to calculate the total spectral short circuit current density for different wavelengths, keeping a constant junction depth. The values of total spectral short circuit current density are then used to calculate spectral response (SR) as well as quantum efficiency (QE).

The total short circuit current density (J_{sc}) is then calculated using the equation shown below, as already been discussed in chapter 2.

The total short circuit current density is

$$J_{sc} = \int_0^\infty J_{sc\lambda}d\lambda = \int_0^\infty (J_{scP}(\lambda) + J_{scN}(\lambda) + J_{dr}(\lambda))\, d\lambda \qquad ...3.6$$

This is then used to calculate open circuit voltage (V_{oc}) using the equation shown below, as already been discussed in chapter 2.

$$\mathrm{V_{OC}} = \frac{\mathrm{kT}}{\mathrm{q}}\ \ln(\frac{J_{sc}}{\mathrm{J_0}} + 1) \qquad ...3.7$$

before that we need to calculate saturation current density (J_0) using equations shown below, as already been discussed in chapter 2.

$$J_{0p} = q\,\frac{D_pn_i^2}{L_pN_d}\frac{\frac{S_pL_p}{D_p}cosh\frac{W_n}{L_p}+sinh\frac{W_n}{L_p}}{\frac{S_pL_p}{D_p}sinh\frac{W_n}{L_p}+cosh\frac{W_n}{L_p}} \qquad ...3.8$$

$$J_{0n} = q\,\frac{D_n n_i^2}{L_n N_a}\,\frac{\frac{S_n L_n}{D_n}\cosh\frac{W_p}{L_n} + \sinh\frac{W_p}{L_n}}{\frac{S_n L_n}{D_n}\sinh\frac{W_p}{L_n} + \cosh\frac{W_p}{L_n}} \qquad \text{...3.9}$$

$$J_0 = J_{0p} + J_{0n} \qquad \text{...3.10}$$

With the value of (J_0) the dark current density is calculated using equation shown below, as already been discussed in chapter 2.

$$J = J_0(e^{-\frac{v}{V_t}} - 1) \qquad \text{...3.11}$$

The voltage increments are in the steps of 1 mV. Then the fill factor is calculated using the equation shown below, as already been discussed in chapter 2.

$$FF = \frac{J_{mp}V_{mp}}{J_{sc}V_{oc}} \qquad \text{...3.12}$$

The FF needs the maximum value of the product of (I-V) which corresponds to the value of maximum power delivered by the cell. Then the efficiency of the cell is calculated using the equation shown below, as already been discussed in chapter 2.

$$\eta = \frac{V_{OC}I_{SC}FF}{P_{in}} \qquad \text{...3.13}$$

The above parameters are again calculated with the same set of input, but with a variable junction depth and constant doping concentration. The code related to this is given in APPENDIX B, B.1

3.2 MODULE 2: ARC coating and Texturing

In this module ARC coating and texturing is employed in the code. An optimum value of doping concentration (Na, Nd, Na+) is taken from the results of the *module 1* and kept constant throughout this module with a variable junction depths. Apart from that the cell structure of 400 um cell thickness with an emitter thickness of 0.1µm and $1cm^2$ area of cross section is considered. Along with the initial structure, the following inputs are given to the code as a text file.

- Wavelength (nm) from 290 nm-1200 nm.
- Absorption coefficient of silicon (cm^{-1}) for different wavelengths in steps of 10 nm.
- Solar irradiance value of AM1.5G [4] in $\mathrm{Watt}/\mathrm{m}^2 - \mathrm{um}$ for different wavelengths in steps of 10 nm.
- Wavelength dependent refractive index of silicon for different wavelengths in steps of 10 nm.

The ARC coating will improve the reflectance of the silicon surface, based on the equation shown below, as already been discussed in chapter 2.

$$\mathrm{R} = \frac{r_1^2 + r_2^2 + 2r_1 r_2 \cos 2\theta}{1 + r_1^2 r_2^2 + 2r_1 r_2 \cos 2\theta} \qquad \text{...3.14}$$

Where,

$$r_1 = \frac{n_0 - n_1}{n_0 + n_1}, r_2 = \frac{n_1 - n_2}{n_1 + n_2} \text{ and } \theta = \frac{2\pi n_1 d_1}{\lambda}$$

The texturing will be employed which will improve the Absorption coefficient of silicon based on the equation shown below, as already been discussed in chapter 2.

$$\alpha^* = \frac{\alpha}{\cos\beta} + \frac{1}{d} \ln[\frac{1-R(1-f)e^{-4\alpha d}}{1-R((1-fe^{-2\alpha d})}] \qquad \text{...3.15}$$

The improved absorption coefficient is called the effective absorption coefficient which will be used in the above equations 3.3, 3.4, 3.5 replacing the previous values of the absorption coefficient of non-textured (plain surface) silicon to obtain the improved values of total spectral short circuit current density for different wavelengths. The values of total spectral short circuit current density are then used to calculate spectral response (SR) as well as quantum efficiency (QE). The total short circuit current density (J_{sc}) is then calculated using the equation 3.6, which is then used to calculate open circuit voltage (V_{oc}) using equation 3.7 before that we need to calculate saturation current density (J_0) using equations 3.8, 3.9, 3.10. Then the fill factor as well as the efficiency of the cell is calculated using equations 3.12, 3.13 respectively. The code related to this is given in APPENDIX B, B.2

3.3 MODULE 3: Series resistance, p+ region thickness (*keeping cell thickness constant*) and overall cell thickness

In this module the resistive effect of the cell is employed in the code. Along with that the p+ region thickness (*keeping cell thickness constant*) and the overall cell thickness is also varied to get an optimum cell structure. So in this code an optimum value of doping concentration (Na, Nd, Na+) is taken from the results of the *module 3* while the junction depth is varied. The cell structure of 400 um cell thickness with an emitter thickness of 0.1μm and $1cm^2$ area of cross section is considered. Along with the initial structure, the following inputs are given to the code as a text file.

- Wavelength (nm) from 290 nm-1200 nm.
- Solar irradiance value of AM1.5G [4] in $\mathrm{Watt}/_{\mathrm{m}^2 - \mathrm{um}}$ for different wavelengths in steps of 10 nm.
- Wavelength dependent refractive index of silicon for different wavelengths in steps of 10 nm.

The short circuit current (J_{sc}), QE, SR, V_{oc}, J_0, FF, efficiency is calculated similar to the *module 3*. After that the resistive losses is calculated. The shunt resistance is considered to be infinite, as it depends on the processing technology while the series resistance is modelled based on the equations given in the table 3.1. So to model the series resistance first a metallic grid structure is considered with ρ_c = 1E-3 ohm-cm^2, resistivity of a metallic grid structure of silver is 1.59E-6 ohm-cm, and its dimensions are considered as follows.

- Spacing between the metal fingers (S) = 520 um.
- Width of the fingers (W_f) = 6 um.
- Width of the busbars (W_{bus}) = 100 um.
- Aspect ratio= 0.2
- Number of bonding points per busbar (n) = 20.

Component	Expression
Emitter	$R_e = \frac{n.S^2}{3L}\frac{R_e}{(L/_2 - W_{bus})}$
Base	$R_b = \rho_{base}\frac{8n.W_p}{L^2} + \rho^{+}_{base}\frac{8n.W_p^{+}}{L^2}$
Metallic finger	$R_f = \frac{n.s}{3L}\frac{\rho_{metal}}{W_f h_f}(L/_2 - W_{bus})$
Bus bar	$R_{bus} = \frac{\rho_{metal}}{3n}\frac{L}{W_{bus}h_{bus}}$
Rear contact resistance	$R_{fc} = \frac{8n.s.\rho_c}{L(W_f.L + 2W_{bus}.(s - W_f))}$
Front contact resistance	$R_{bc} = \frac{8n.\rho_c}{L^2}$

Table 3.1 Analytical expressions of the series resistance components for a two bus-bar cell

By calculating all the expressions given in the table above, the series resistance of the cell is determined by the equation shown below, as already been discussed in chapter 2.

$$R_S = \frac{\sum R_{components}}{8n} \qquad ...3.16$$

along with this the recombination current at the space charge region of the solar cell is also calculated using equation shown below, as already been discussed in chapter 2.

$$I = I_{02}(e^{\frac{q(v+IR_S)}{2kT}} - 1) \qquad ...3.17$$

Both these values are then used in the equation shown below to get a current- voltage relation of the solar cell, as already been discussed in chapter 2.

$$I = I_L - I_0(e^{[\frac{q(v+IR_S)}{kT}]} -1) - I_{02}(e^{[\frac{q(v+IR_S)}{kT}]}) \qquad ...3.18$$

The voltage increments are in the steps of 1 mV. Then the fill factor is calculated using the above equations 3.12, which needs the maximum value of the product of (I-V) which corresponds to the value of maximum power delivered by the cell. Then the efficiency of the cell is calculated using equation 3.13.

Calculation of all the parameters which are determined until now in the module 4 are repeated again by varying p+ region thickness as well as the cell thickness to get a maximum value of the efficiency which corresponds to a particular cell structure and that structure is called the optimum cell structure for a single junction silicon solar cell. The code related to this is given in APPENDIX B, B.3

Chapter 4

MATLAB SIMULATION OF SOLAR CELL

The theory behind the simulation of the solar cell, the corresponding models used and the essential parameters which need to be varied (*i.e. doping concentrations, junction depth, p+ region thickness and finally thickness of the solar cell*) was explained in earlier chapter. As has been already discussed, the program has been written in the MATLAB in three modules. This chapter is divided into four sections; first section includes the simulation of module 1 which deals with the effect of variation in doping and junction depth on the cell performance. The next section includes the simulation of module 2 which deals with the ARC coating and the texturing of the cell, the third section deals with the simulation of module 3 which includes the resistive effects of the cell. It also includes the effects of variation in p+ region thickness and the overall cell thickness, the last section deals with the characteristic of the final solar cell which has been optimised based on the simulation performed in three modules.

4.1 MODULE 1 SIMULATION

The solar irradiance AM1.5G will give the number of photons incident on the solar cell at each wavelength per unit surface per second which is called the photon flux as given in *equation 2.11*. The incident photons are absorbed into the cell exponentially as given in *equation 2.1*, depending upon the absorption coefficient of silicon at each wavelength as shown in *figure 2.2*. So the photons incident on the top surface of the cell gets absorbed in three different regions i.e. the emitter, base and depletion regions depending upon its wavelength. The absorbed photons will then generate electron hole pairs in those corresponding regions and these electron hole pairs will get separated if they are in the depletion region or within the diffusion length of the minority carriers, around the depletion region because of the electric field in the depletion region. These separated electron hole pairs will results in the spectral short circuit current density in different regions as given in equations 2.12, 2.13, 2.14; adding all the three equation will give spectral short circuit current density, adding further over the entire wavelengths (290nm-1200nm) will give the total short circuit current density as given in equation 2.15.

The doping concentrations are varied, from Na= $1E15cm^{-3}$ to Na= $1E18cm^{-3}$, Nd= $1E15cm^{-3}$ to Nd= $1E19cm^{-3}$ keeping Na+= $1E19cm^{-3}$ constant as well as junction depth(W_n) = 0.1 µm. High base doping decreases the minority carrier diffusion length in the base so the recombination will increase in base, it also increases the recombination velocity at the P/P+ which will reduce the Jsc. While low base doping increases the minority carrier diffusion length in the base and reduces the surface recombination velocity at the P/P+ interface which will enhance the Jsc but very low values will decrease the number of carriers generated in the base region and hence Jsc. Now keeping high emitter doping will increase the Jsc as it will increase the number of carriers generated in the emitter. But too high values will reduce the Jsc if the condition ($L_p > W_n$) is not satisfied because the generated carriers in the emitter will recombine within the emitter region before being collected at the junction if

$(L_p < W_n)$. Low values of Nd will decrease the number of carriers generated in the emitter region and hence Jsc.

The Voc scales logarithmically with the short circuit current as well as reverse saturation current. While J_{sc} typically has a small variation, the key effect is the saturation current density, since this may vary by orders of magnitude. The saturation current density, J_0 depends on doping concentration of the solar cell. High dopings will decrease the minority carrier concentrations in the cell and hence the saturation current density J_0 as shown in equation 2.19 and equation 2.21. While Voc increases logarithmically as the reverse saturation current decreases, this will also increase the fill factor as it depends mainly on Voc as given in equation 2.26. The efficiency of the cell mainly depends on the short circuit current and Voc as shown in equation 2.29. The results of all these variations are shown below.

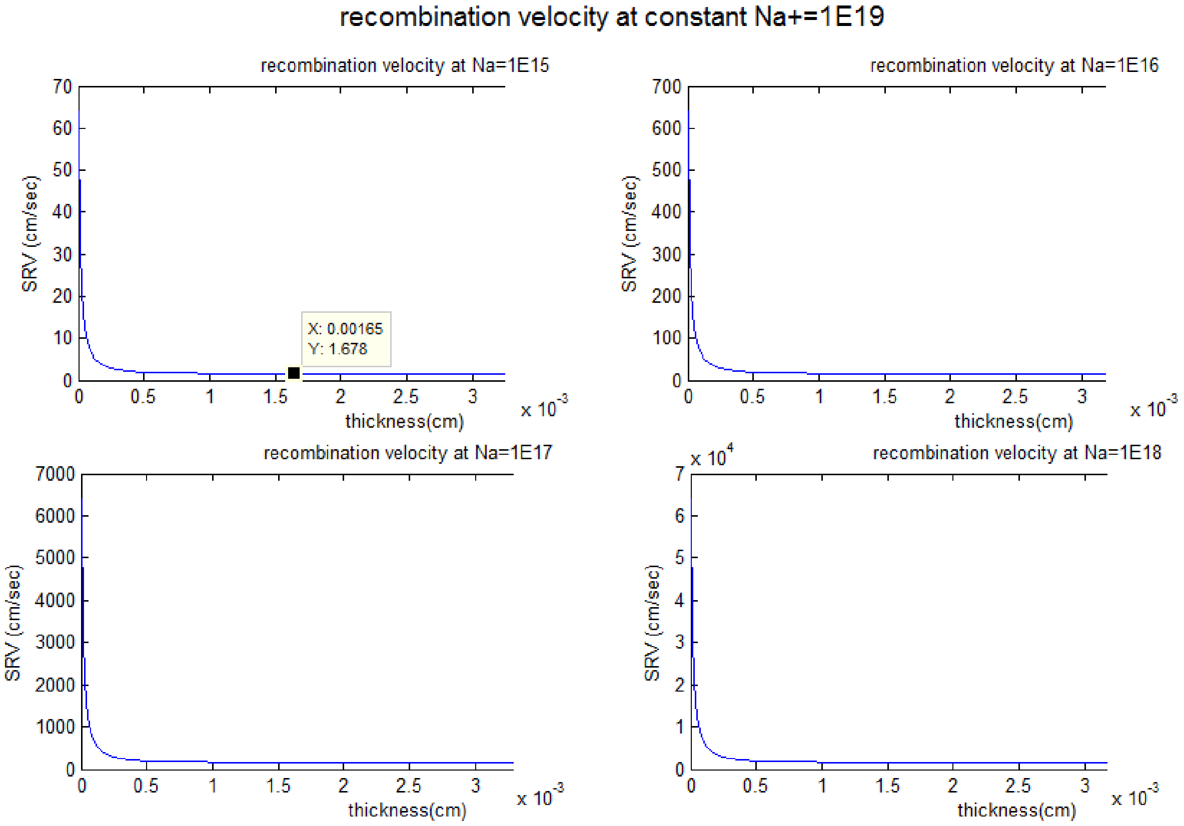

Figure 4.1 recombination velocity Vs. P+ thickness for constant Na+ and different Na

The above figure shows that surface recombination velocity=1.678 cm/sec is minimum for Na=1E15 with a p+ layer thickness of 16.5 µm,

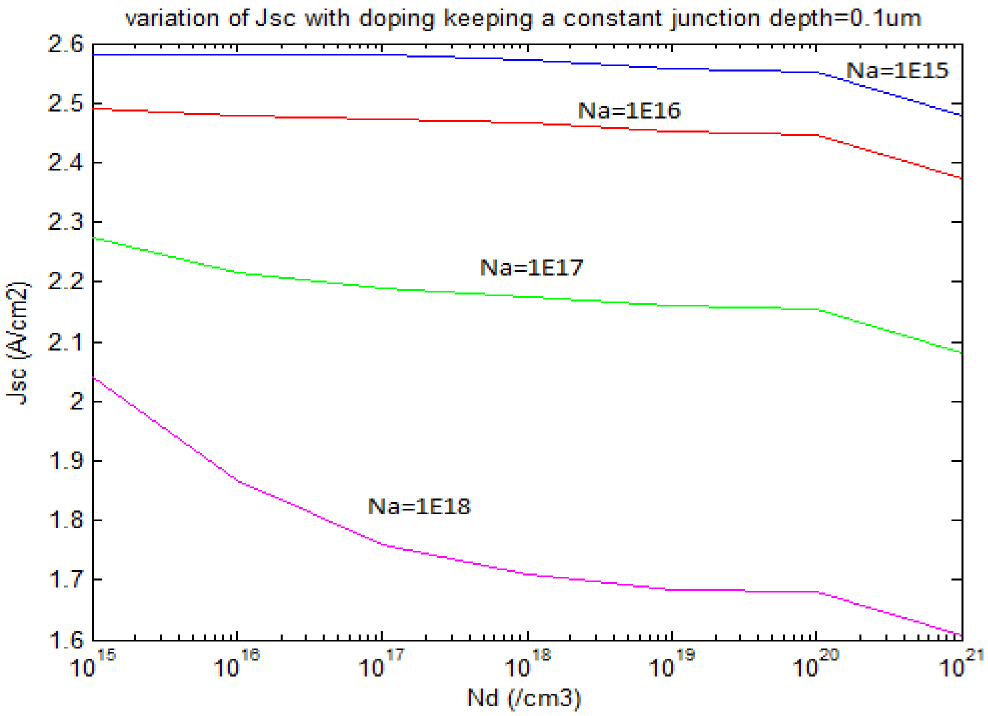

Figure 4.2 variation of Jsc with Nd keeping Na constant

The above figure shows that the Jsc is maximum at Na=1E15 cm^{-3} Nd = 1E20 cm^{-3}

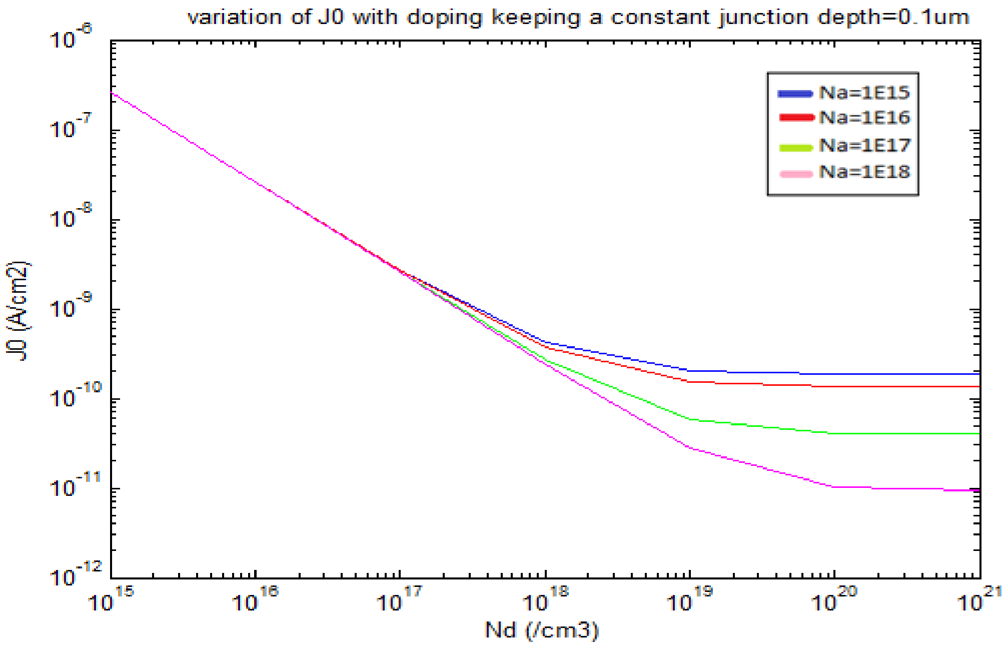

Figure 4.3 variation in J_0 *with Nd keeping Na constant*

The above figure shows that the J_0 is minimum at Na=1E15cm^{-3} and Nd=1E20cm^{-3}

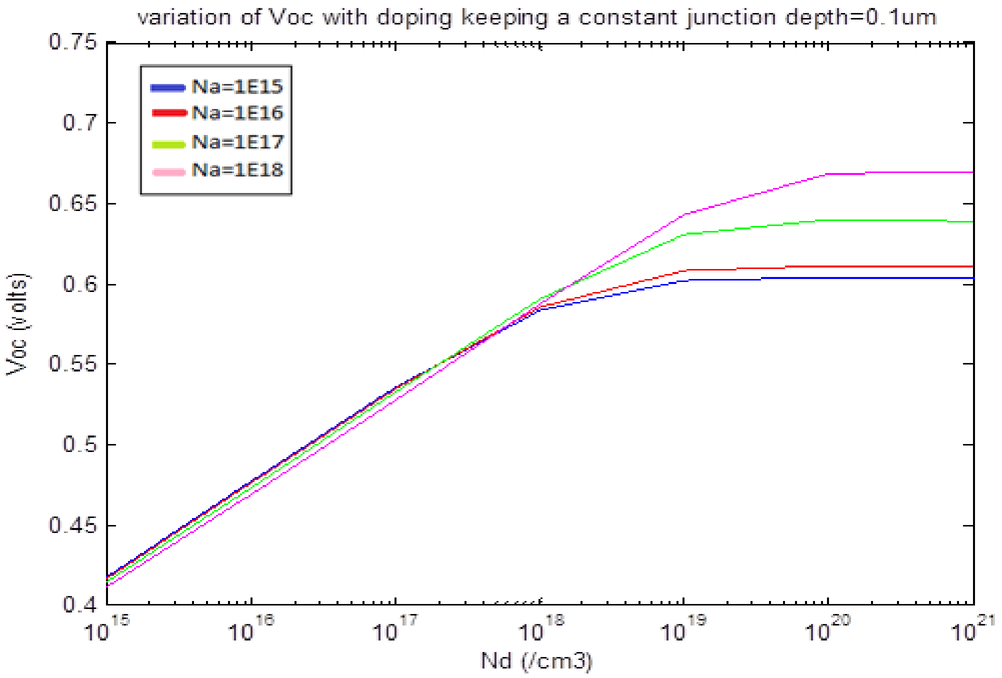

Figure 4.4 variation in Voc with Nd keeping Na constant

The above figure shows that the Voc is maximum at Na=1E18 cm^{-3} and Nd=1E20 cm^{-3} and almost gets saturated with further increase in Nd.

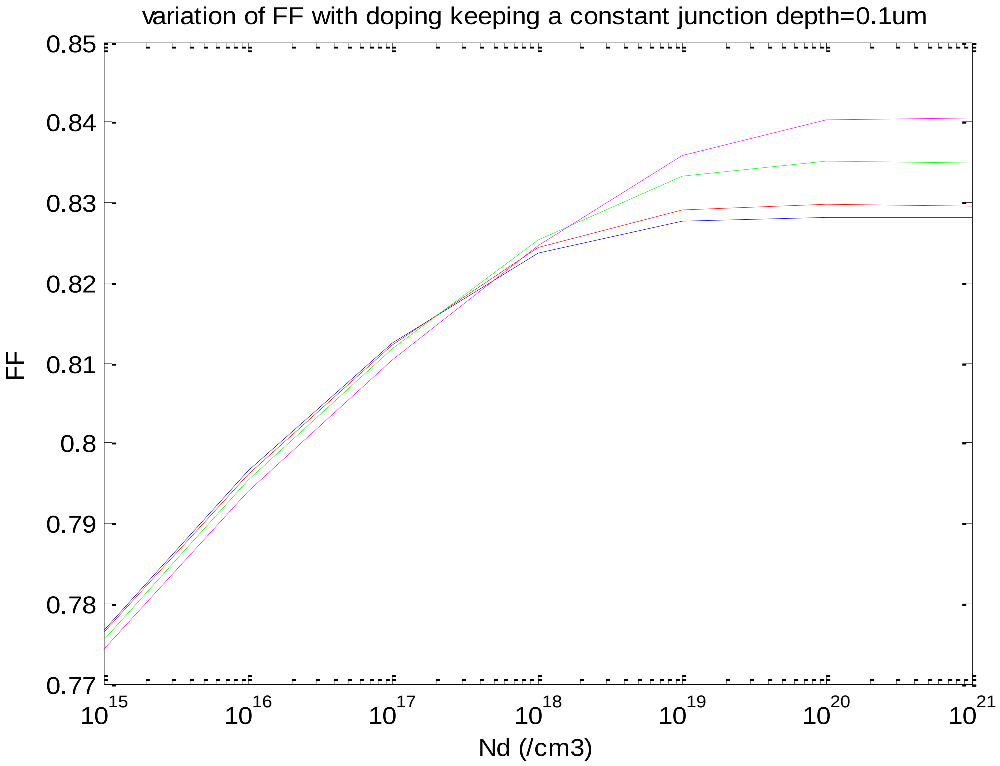

Figure 4.5. variation in FF with Nd keeping Na constant

The above figure shows that the FF is maximum at Na=1E15 cm^{-3} and Nd=1E20cm^{-3} and then gets almost saturated similar to the Voc graph above. It shows that FF is dependent mainly on Voc.

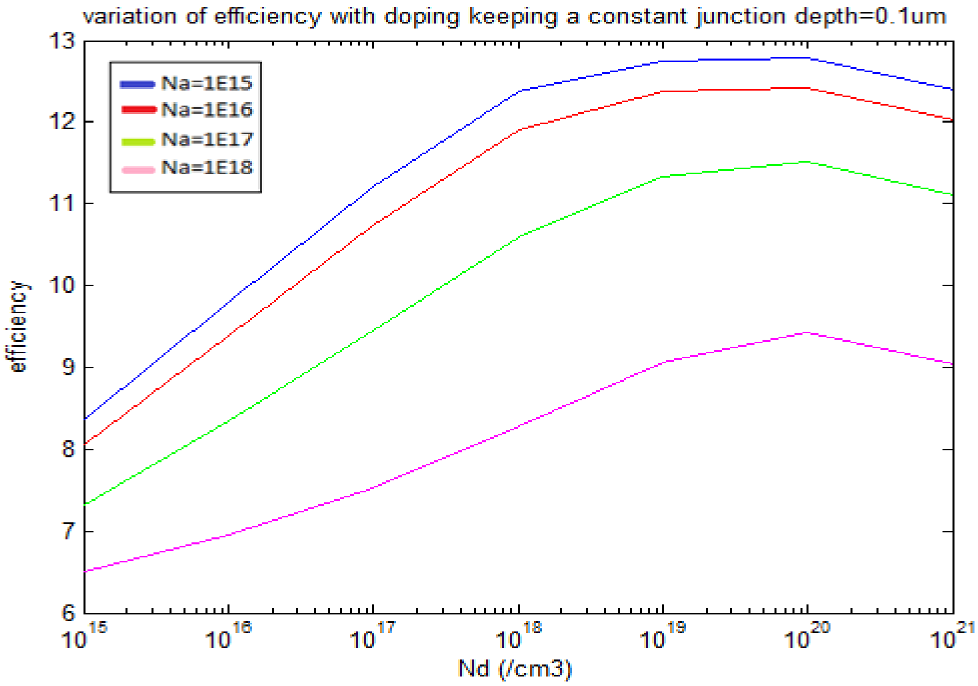

Figure 4.6 variation in efficiency with Nd keeping Na constant

The above figure shows that the efficiency is maximum at Na=1E15 cm^{-3} and Nd=1E20 cm^{-3}

By varying the doping concentrations, the maximum efficiency of 12.779 % can be achieved at Nd=1E20 cm^{-3}, Na=1E15 cm^{-3}, Na+=1E19 cm^{-3}, which is quite a low value and can be improved by further reducing the junction depth as it will improve the collection probability as shown in *figure 2.4*.

Now, the junction depth is varied, from 0.05 um to 1 um keeping the doping concentrations constant at Nd=1E20cm^{-3}, Na=1E15cm^{-3}, and Na+=1E19cm^{-3}. The deeper junction depths will reduce the Jsc, as most of the generated carriers in the emitter will recombine within the emitter region before being collected by the junction. While the shallower junction depths will also reduce the Jsc, as the recombination at the surface is high and keeping the junction very close to the surface will certainly reduce the collection probability.

The Voc scales logarithmically with the short circuit current density as well as reverse saturation current density as shown in equation 2.24. The saturation current remains constant as it is independent of the variation in junction depth so Voc will depends only on short circuit current density Jsc. So, Voc decreases logarithmically as the short circuit current decreases, this will also decreases the fill factor as it depends mainly on Voc as given in equation 2.26. The efficiency of the cell mainly depends on the short circuit current and Voc as shown in equation 2.29. The results of all these variations are shown below.

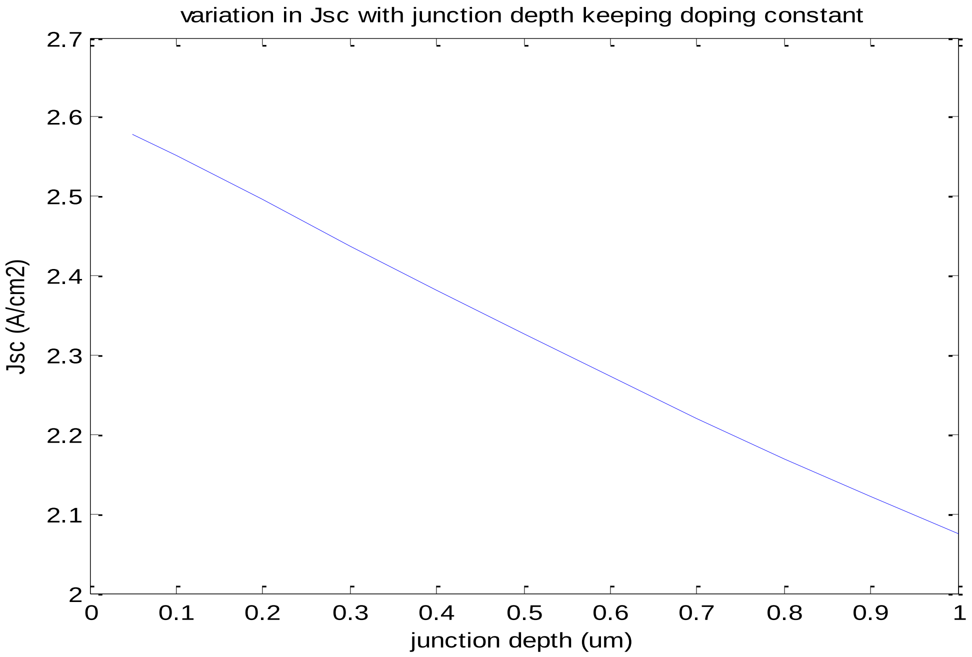

Figure 4.7 variation of Jsc with junction depth

The above figure shows that Jsc is maximum at the junction depth of 0.05 um, as the generation rate of carriers is higher at the top surface, which falls exponentially with the distance from the surface, so more closely the junction to the top surface, more number of carriers will be collected.

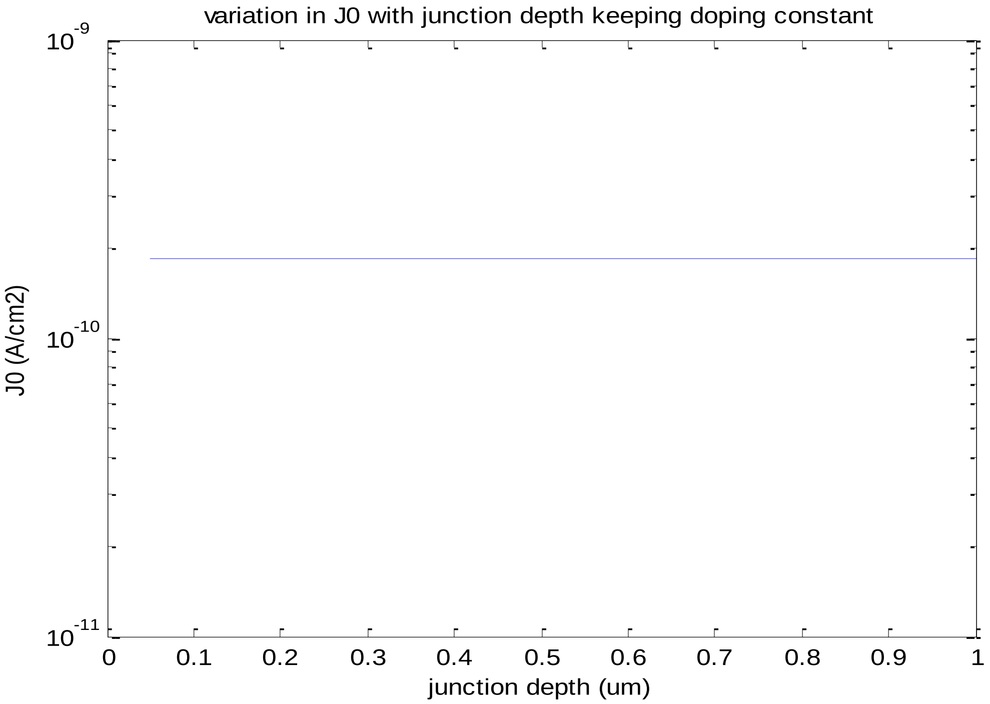

Figure 4.8 variation of J_0 *for different junction depths*

The above figure shows that J_0 remains constant, as it dependent on doping concentration, diffusion length and diffusion coefficient which are independent of junction depth.

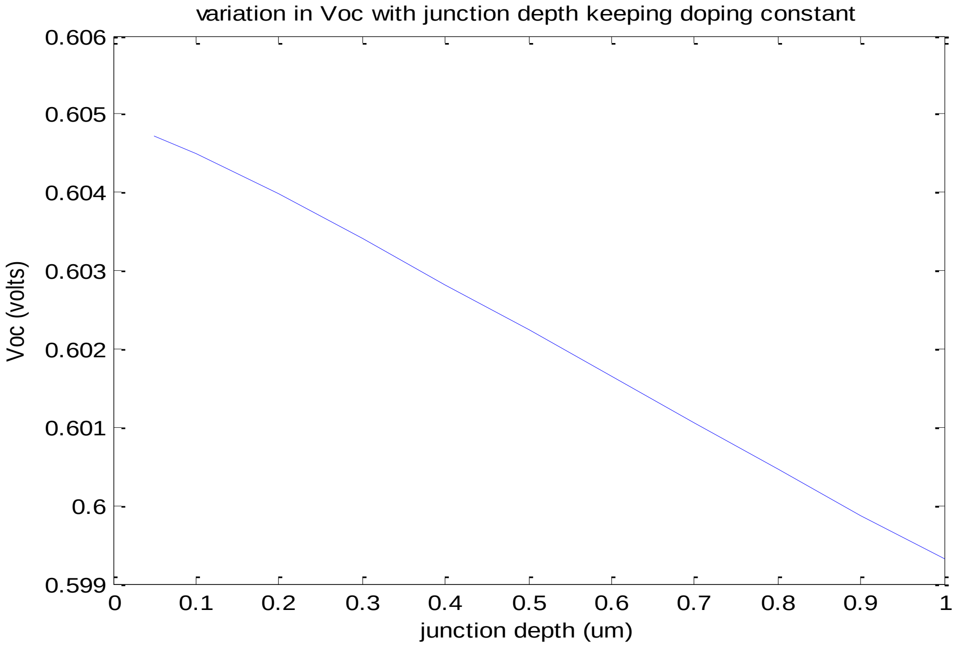

Figure 4.9 variation of Voc for different junction depths

The above figure shows that Voc is maximum at the junction depth of 0.05 um and starts decreasing with increase in junction depth, similar to Jsc curve. This is because Voc is logarithmically dependent on Jsc and J_0. Since the J_0 is constant here. So the effect of Jsc is dominant.

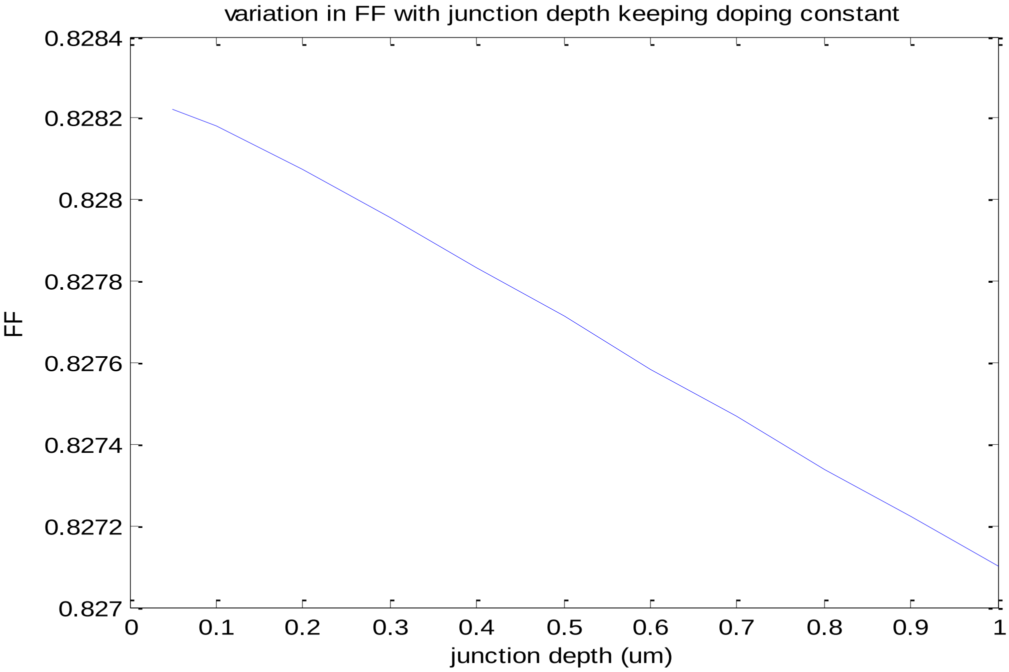

Figure 4.10 variation of FF for different junction depths

The above figure shows that FF is maximum at the junction depth of 0.05 um and starts decreasing with increase in junction depth similar to the Voc graph above. It shows that FF is dependent mainly on Voc.

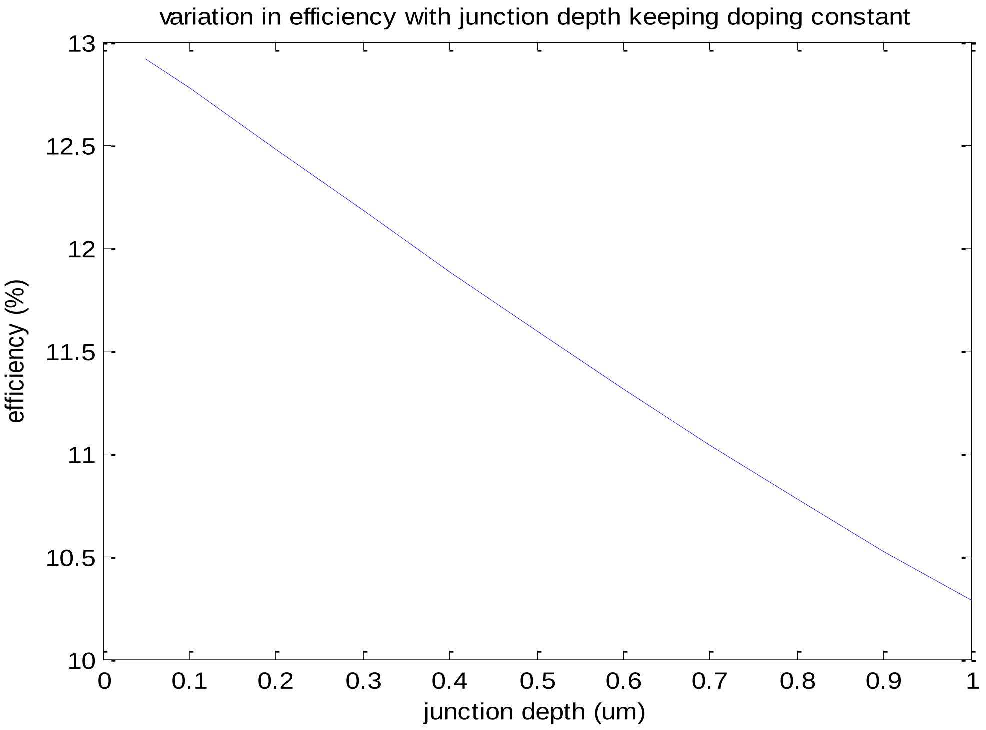

Figure 4.11 variation of efficiency for different junction depths

The above figure shows that the efficiency is maximumum at the junction depth of 0.05 um and it starts reducing with increase in the junction depth, as Jsc and Voc decreases with increase in junction depth.

4.2 MODULE 2 SIMULATION

Now, to increase the efficiency further we need to reduce the reflectance of the silicon surface so that the intensity of the light enters into the cell will increase. This can be done by using an ARC coating whose refractive index would be the geometric mean of the refractive index of air as well as silicon, which will be closer to the refractive index of Si_3N_4 (i.e. 2.01) and the thickness of the ARC will be optimised to 76.948 nm (*calculated using equation 2.30*), to get zero reflectance at 600nm wavelength, since the solar spectrum AM1.5G peaks at this wavelength as shown in figure 2.6. In addition to that we need to increase the absorption of photons by the silicon particularly at longer wavelengths which are otherwise weakly absorbed; this can be done by increasing the optical path length of the photons inside the cell with texturing as shown in figure 2.13. So, the texturing as well as ARC coating will increase the Jsc by increasing the absorption coefficient of the cell which is called effective absorption coefficient as shown in the equation 2.33 and hence increases Voc, FF and efficiency. The results of all these variations are shown below.

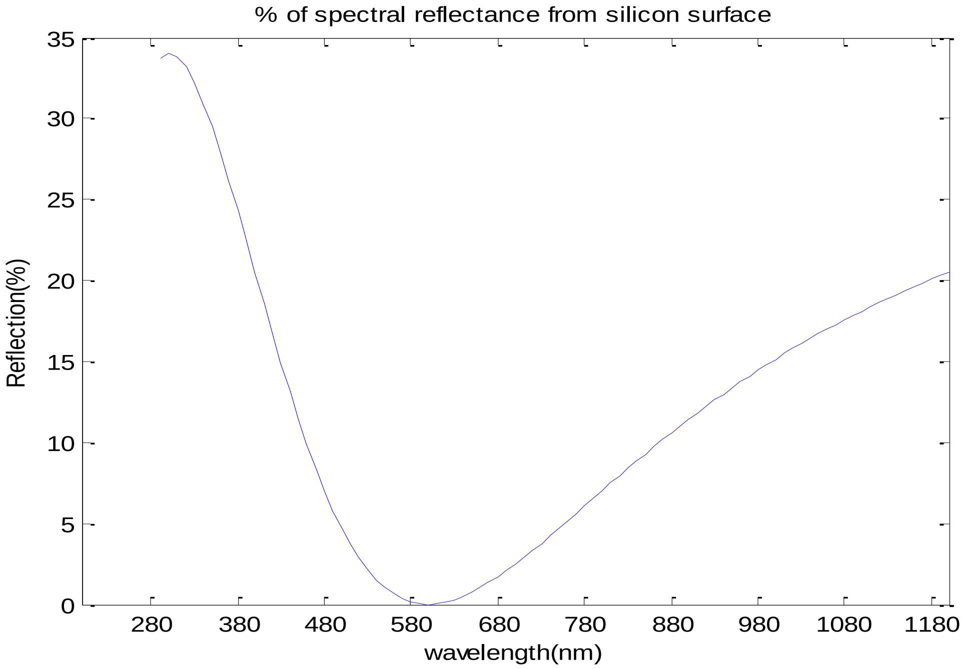

Figure 4.12 reflectance of incident light of different wavelength from the surface of silicon

The above figure shows that the reflectance is zero at 600nm.

Texturing at front surface is done with a face angle (2θ) =70.53°
Lambertian reflector at the back with reflectance of 97%

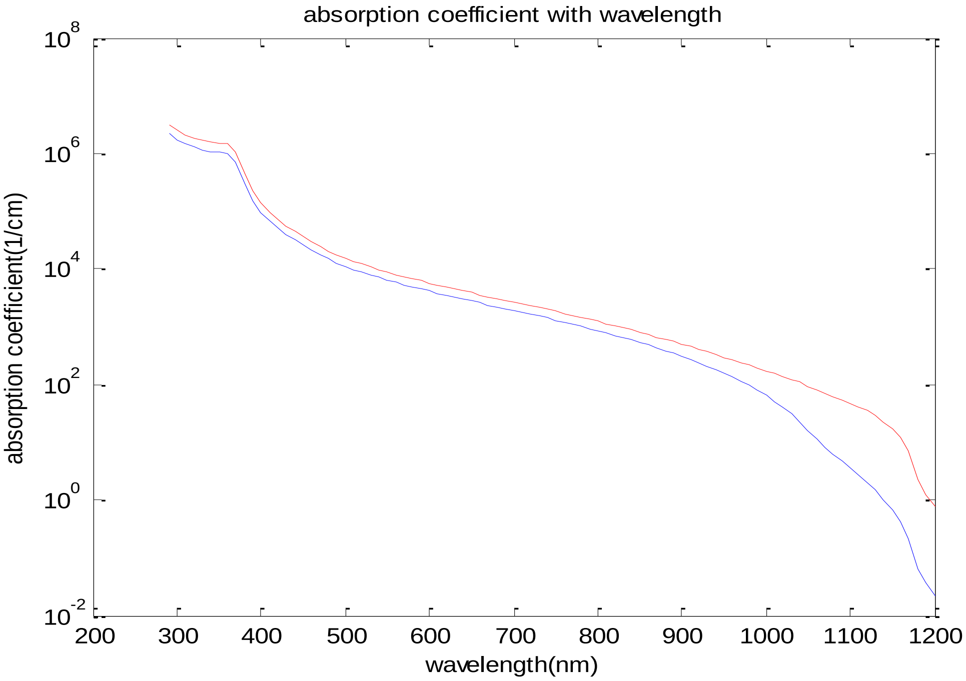

Figure 4.13 comparison between absorption coefficient (blue) and effective absorption coefficient (red) of silicon vs. wavelength

In above figure blue curve is the absorption coefficient of bare silicon without any texturing while the red curve is the effective absorption coefficient as the texturing improves the optical path length of the light inside the cell.

For: Na $=1E15cm^{-3}$, Nd $=1E20cm^{-3}$, Na+ $=1E19cm^{-3}$

Emitter thickness (µm)	**Jsc (amps/cm2)**	**Voc (Volts)**	**FF**	**Efficiency**
0.05	4.0188	0.6161	0.8305	20.5634
0.1	4.0093	0.6160	0.8305	20.5121
0.2	3.9674	0.6157	0.8305	20.2869
0.3	3.8955	0.6152	0.8304	19.9008
0.4	3.8003	0.6146	0.8302	19.3909
0.5	3.6909	0.6138	0.8301	18.8056
1	3.1390	0.6096	0.8292	16.4029

Table 4.1 Values of Jsc, Voc, FF and efficiency with different emitter thickness

From table 4.1 it can be observed that the value of Jsc, Voc , FF and efficiency is greatly improved.

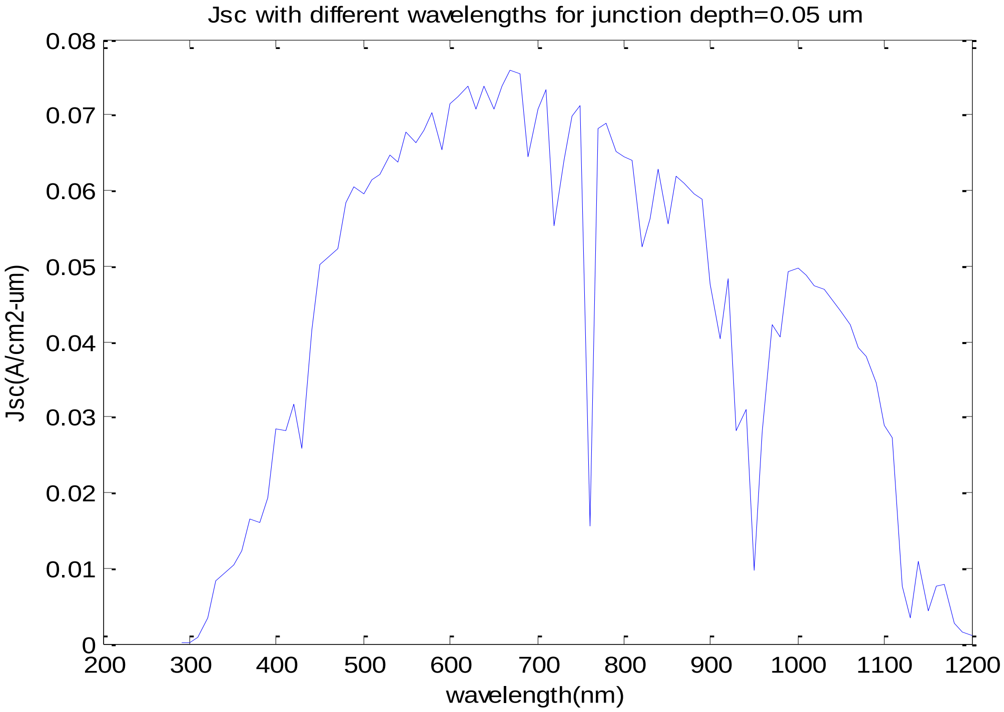

Figure 4.14 short circuit current density Vs. wavelength for emitter thickness=0.05 µm

The above figure shows the spectral short circuit current density, it shows that the short circuit current is higher at around 670 nm.

4.3 MODULE 3 SIMULATION

Now, the resistive losses (*series and shunt resistance*) of the solar cell are included. The shunt resistance (Rsh) is considered to be infinite as it depends on the process technology. The series resistance is modelled using the equations given in table 2.1. The series resistance will reduce the current delivered by the cell as well as the voltage across the cell, which will decrease the power delivered by the solar cell and hence the efficiency of the cell. In addition to that the recombinations at the space charge region of the cell, which are significant at low voltages are also included, which can be modelled by including saturation current density (J_{02} or I_{02}) with an ideality factor of 2, in the I-V equation of the solar cell as given in equation 2.41. This will further reduce the current and hence the efficiency of the cell. High values of resistance will give very low currents or no current at all. To reduce the resistance, the base doping 'Na' will be increased to Na=$1E16cm^{-3}$from Na=$1E15cm^{-3}$; which will reduce the base resistance. To reduce the resistance further thickness of p+ region can be increased (*keeping cell thickness constant*). The overall thickness of the cell can also be decreased, to reduce the series resistance further, which will enhance the current as the carrier generated within the cell are closer to the junction and hence the efficiency of the cell will be improved. But reducing the cell thickness below a certain limit will decrease the efficiency as the leakage of light through the cell will increases. The results of all these variations are shown below.

For: Na=$1E15cm^{-3}$, Nd=$1E20$, Na+=$1E19cm^{-3}$

Thickness of the cell= 400μm
Thickness of P+ region is 16.5 μm
Surface recombination velocity at p/p+ interface 1.678 (cm/sec).

Series resistance of this cell structure is 167.65 mΩ which is high for a $1cm^2$ area cell. To reduce the series resistance thickness of p+ region should be increased.

Thickness of p+ region(μm)	**Series resistance (mΩ)**
16.5	167.65
100	130.1
200	85.12
300	40.14
377	14.731

Table 4.2 Values of series resistance with different p+ region thickness

From the above table it can be observed that the series resistance of the cell will decreases with increase in the thickness of p+ layer (*keeping cell thickness constant*). For a 377μm thick p+ region the cell delivers some current at an efficiency of (18.84%) which is very low.

To improve the series resistance of the cell, doping of base is increased to Na=16cm^{-3}. Doping of emitter layer is kept same at Nd=20 cm^{-3}

Thickness of p+ region(μm)	**Series resistance (mΩ)**	**Efficiency (%)**
100	19.644	15.0041
200	15.785	18.1839
300	12.278	19.7178
342	12.021	19.876
377	10.277	19.1031

Table 4.3 Values of series resistance and efficiency with different p+ region thickness

For: Na=1$E16cm^{-3}$, Nd=1$E20$, Na+=1$E19cm^{-3}$

Maximum efficiency of 19.876% can be achieved with 342μm thick p+ layer. For the same cell structure the efficiency is 21.8836% without considering any resistive and recombination losses in the cell.

The series resistance of the cell can be further reduced by reducing the cell thickness which will improve the solar cell efficiency.

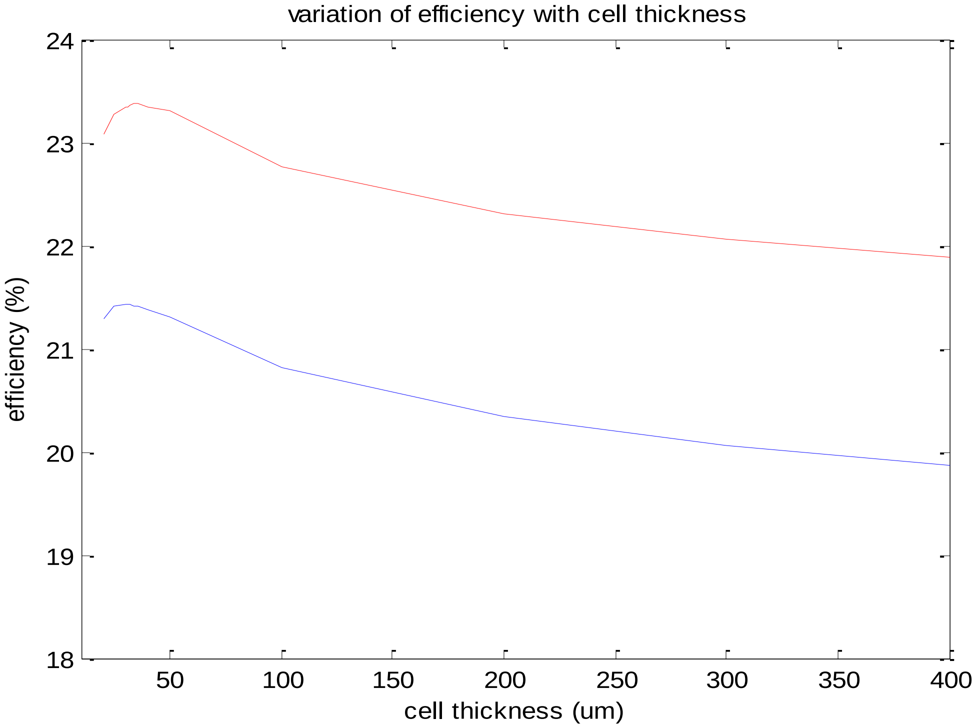

Figure 4.15 efficiency with resistive losses (blue), efficiency without resistive losses (red) Vs. cell thickness

The above figure shows that, efficiency is highest for 31 μm thick cell. The efficiency will increase as the cell thickness decreases but the efficiency starts reducing if the cell thickness decreases below 31 μm.

4.4 CHARACTERISTICS OF THE FINAL SOLAR CELL WHICH HAS BEEN OPTIMISED BASED ON THE SIMULATION PERFORMED ABOVE

Based on the simulation of the single junction silicon solar cell performed above, the maximum efficiency achieved is 21.4256% for a 31 µm thick solar cell. The optimum structure of this cell is shown below.

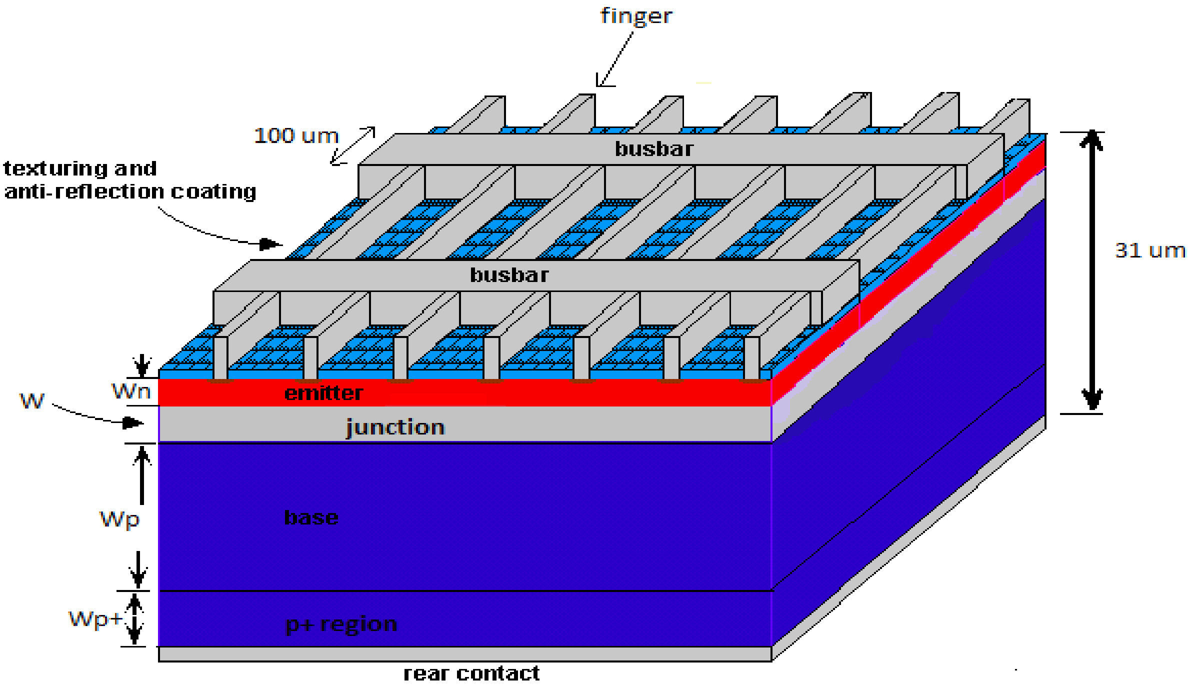

Figure 4.16 single junction silicon solar cell structure

Junction thickness (cm)	3.5149E-04
Junction thickness in N region (cm)	3.5145E-08
Junction thickness in P region (cm)	3.5145E-04
Thickness of N region (cm)	0.2E-04
Thickness of P region (cm)	20.285E-04
Thickness of p+ region (cm)	7E-04
Fill factor	0.78655
Efficiency of the cell	21.4256
Series resistance (mΩ)	10.326
Spacing between metal fingers (cm)	520E-04
Width of the metal fingers (cm)	6E-04
Thickness of metal fingers (cm)	1.2E-04
Width of the busbar (cm)	100E-04
Thickness of busbar (cm)	20E-04

Table 4.4 values of structural parameter of the cell along with its efficiency and FF

For the above cell structure the efficiency without considering resistive and recombination loss is 23.3505%.

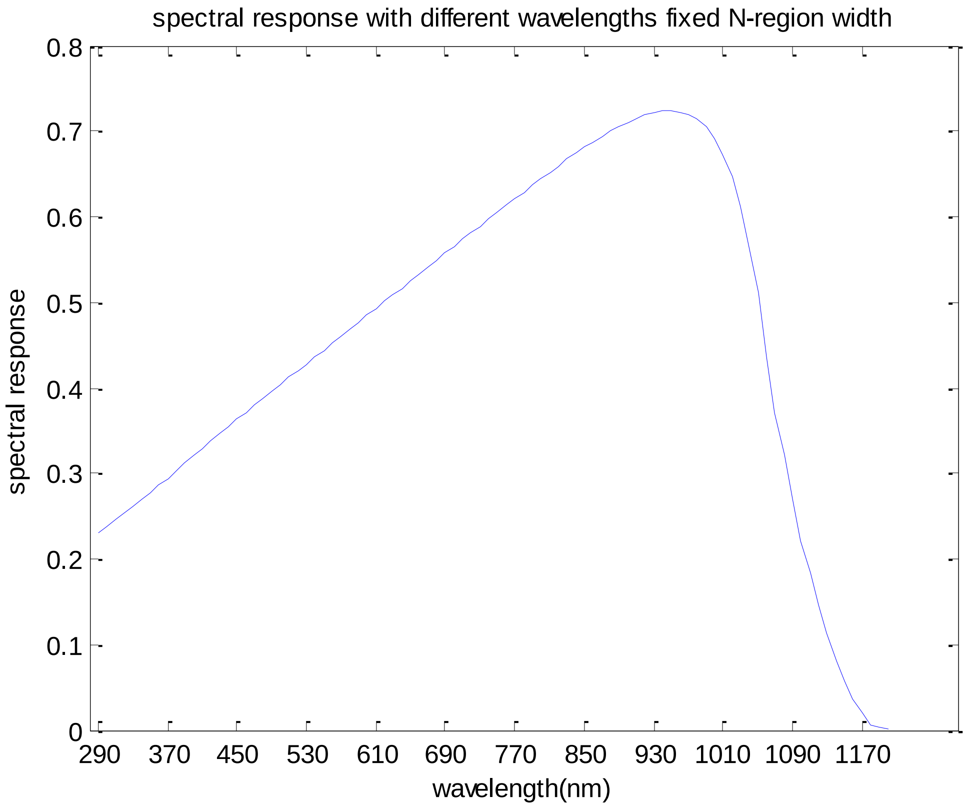

Figure 4.17 spectral response Vs. wavelength for emitter thickness=0.2 µm

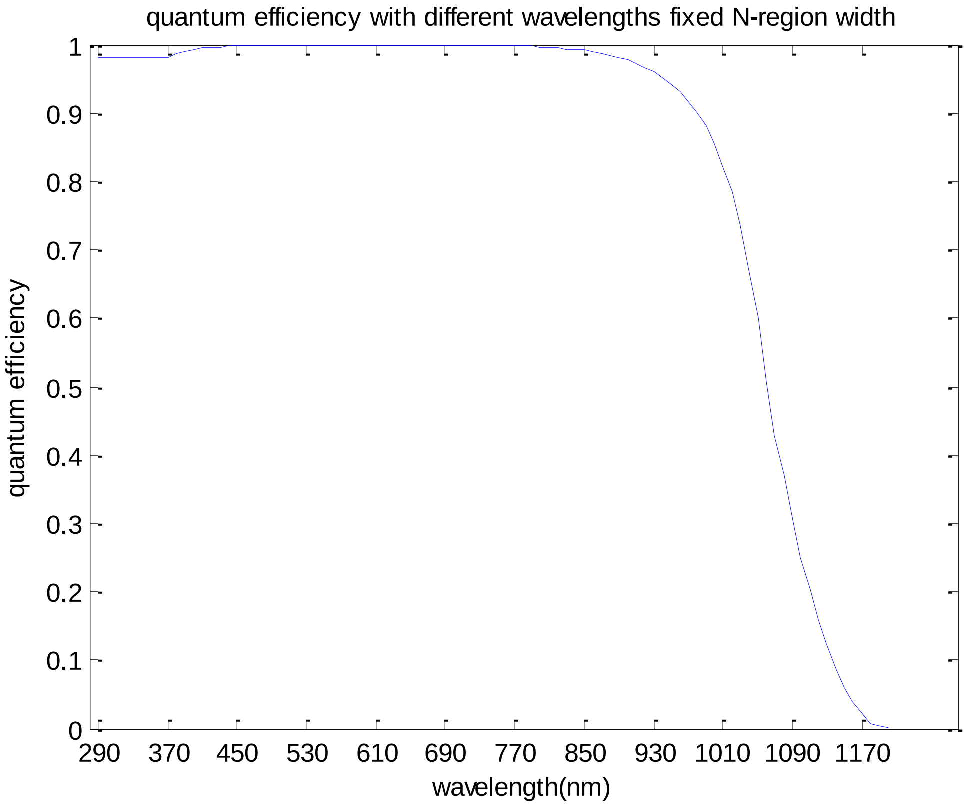

Figure 4.18 quantum efficiency Vs. wavelength for emitter thickness=0.2 µm

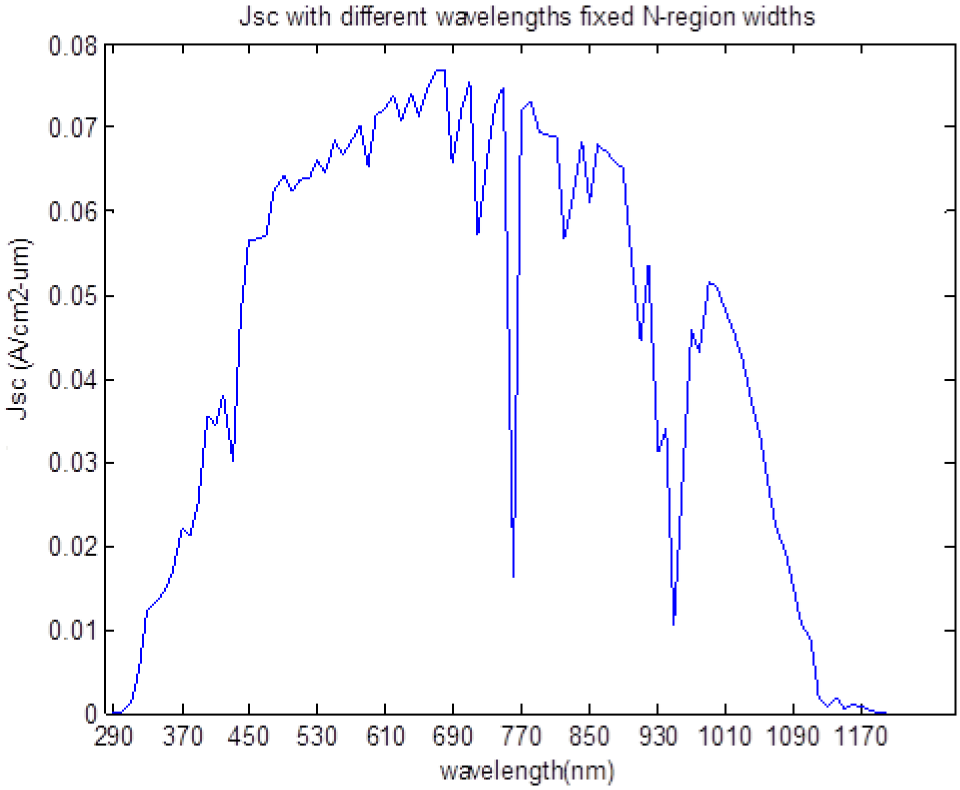

Figure 4.19 short circuit current density Vs. wavelength for emitter thickness=0.2 µm

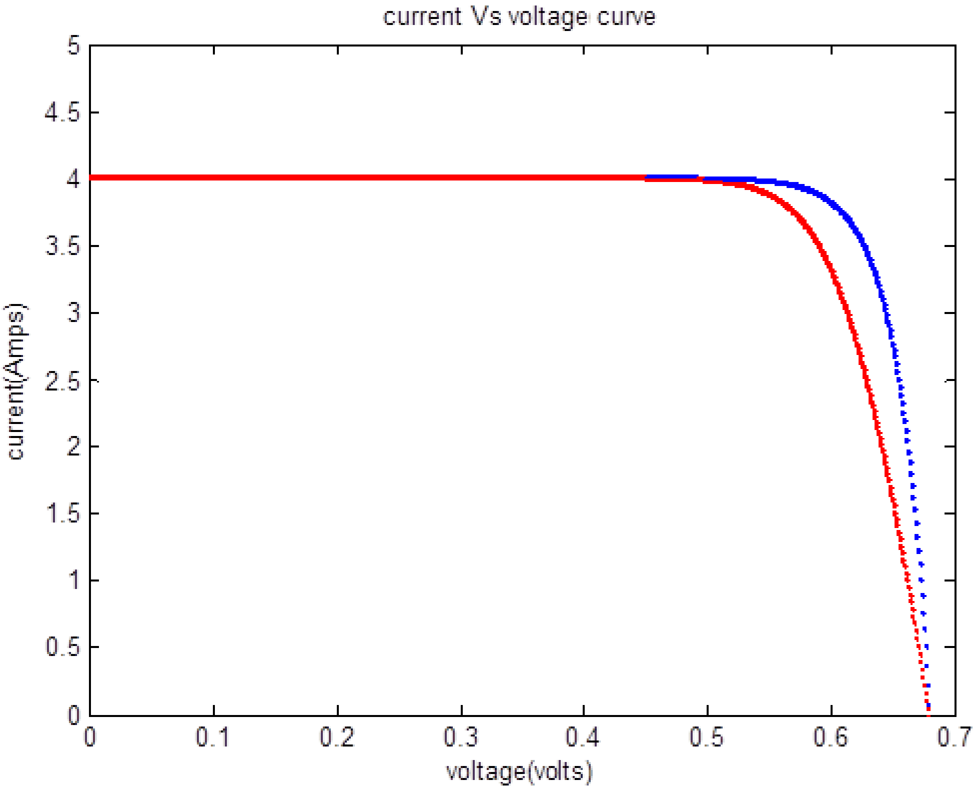

Figure 4.20 current without losses (blue), current with losses (red) vs. wavelength, for emitter thickness=0.2 µm

Chapter 5

CONCLUSION AND FUTURE WORK

5.1 CONCLUSION

This chapter summarizes the key features of this work and its results. In this work a single junction silicon solar cell is modelled and simulated to get an optimum structure of the cell using MATLAB.

Initially a (n p p+) cell structure of 400μm thickness and $1cm^2$ area, was considered with initial dopings of Na=10E15cm^{-3}, Nd=10E15cm^{-3}, Na+=10E19cm^{-3} respectively under a standard solar spectrum model of air mass 1.5 (AM1.5G). The simulation of this structure is carried out to study the effect of variation in doping concentrations and then the variation in junction depth, on the solar cell parameters such as (Jsc, Voc, SR etc.)

The optimised structure is then simulated, with ARC coating and texturing at the front surface and Lambertian reflector at the back, to get the enhanced efficiency.

The same structure is then simulated again, by including the resistive losses of the cell, along with the recombination losses in the depletion region and an optimised metallic grid. As the resistance was high, doping was increased, p+ layer thickness was varied (*keeping cell thickness constant*) and finally the cell thickness was varied to get a cell structure with maximum efficiency.

The cell with 31μm thickness, 0.2μm emitter thickness, 3.5μm junction thickness, 20.285 μm base thickness and 7 μm p+ thickness with doping concentration of Na=1E16cm^{-3} Nd=1E20cm^{-3} Na+=1E19cm^{-3} has the highest efficiency of 21.4.

5.2 FUTURE WORK

This work can be further extended for improving the efficiency of the single junction silicon solar cell by including multiple ARC coatings, by including better model for texturing and lambertian reflector. Efficiency can be further improved by using transparent conductor for contacts instead of metallic grid. The shunt resistance can be included in the model for better accuracy in the efficiency.

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APPENDIX-A

Wavelength (nm)	Absorption coefficient (cm^{-1})	Reflectance	Solar irradiance AM1.5G $\mathrm{Watt}/\mathrm{m}^2 - \mathrm{um}$	refractive index of silicon
290	2.24E+06	0.684235	6.02E-09	4.426
300	1.73E+06	0.623488	1.02E-03	5.055
310	1.44E+06	0.590476	5.09E-02	5.074
320	1.28E+06	0.57413	2.05E-01	5.102
330	1.17E+06	0.565677	4.71E-01	5.179
340	1.09E+06	0.561749	5.02E-01	5.293
350	1.04E+06	0.56538	5.28E-01	5.483
360	1.02E+06	0.582911	5.98E-01	6.014
370	6.97E+05	0.584271	7.55E-01	6.863
380	2.93E+05	0.546502	7.01E-01	6.548
390	1.50E+05	0.510974	7.97E-01	5.976
400	9.52E+04	0.486021	1.11E+00	5.587
410	6.74E+04	0.466853	1.05E+00	5.305
420	5.00E+04	0.451522	1.12E+00	5.091
430	3.92E+04	0.439123	8.75E-01	4.925
440	3.11E+04	0.428907	1.35E+00	4.793
450	2.55E+04	0.419586	1.56E+00	4.676
460	2.10E+04	0.411486	1.53E+00	4.577
470	1.72E+04	0.404281	1.51E+00	4.491
480	1.48E+04	0.397879	1.62E+00	4.416
490	1.27E+04	0.391965	1.62E+00	4.348
500	1.11E+04	0.387106	1.55E+00	4.293
510	9.70E+03	0.382265	1.55E+00	4.239
520	8.80E+03	0.377999	1.52E+00	4.192
530	7.85E+03	0.374142	1.54E+00	4.15
540	7.05E+03	0.370429	1.48E+00	4.11
550	6.39E+03	0.367336	1.54E+00	4.077
560	5.78E+03	0.364216	1.47E+00	4.044
570	5.32E+03	0.361452	1.48E+00	4.015
580	4.88E+03	0.358667	1.50E+00	3.986
590	4.49E+03	0.356345	1.37E+00	3.962
600	4.14E+03	0.354107	1.48E+00	3.939
610	3.81E+03	0.351854	1.47E+00	3.916
620	3.52E+03	0.349785	1.47E+00	3.895
630	3.27E+03	0.348201	1.39E+00	3.879
640	3.04E+03	0.346411	1.43E+00	3.861
650	2.81E+03	0.344714	1.36E+00	3.844
660	2.58E+03	0.343309	1.40E+00	3.83
670	2.38E+03	0.341799	1.42E+00	3.815
680	2.21E+03	0.340282	1.40E+00	3.8
690	2.05E+03	0.338962	1.18E+00	3.787
700	1.90E+03	0.337639	1.28E+00	3.774
710	1.77E+03	0.336413	1.32E+00	3.762

720	1.66E+03	0.335286	9.86E-01	3.751
730	1.54E+03	0.334258	1.13E+00	3.741
740	1.42E+03	0.33333	1.22E+00	3.732
750	1.30E+03	0.332401	1.23E+00	3.723
760	1.19E+03	0.331469	2.66E-01	3.714
770	1.10E+03	0.330535	1.16E+00	3.705
780	1.01E+03	0.329598	1.16E+00	3.696
790	9.28E+02	0.328764	1.09E+00	3.688
800	8.50E+02	0.328033	1.07E+00	3.681
810	7.75E+02	0.3273	1.06E+00	3.674
820	7.07E+02	0.326671	8.62E-01	3.668
830	6.47E+02	0.326041	9.16E-01	3.662
840	5.91E+02	0.32541	1.02E+00	3.656
850	5.35E+02	0.324778	8.94E-01	3.65
860	4.80E+02	0.324145	9.88E-01	3.644
870	4.32E+02	0.323511	9.68E-01	3.638
880	3.83E+02	0.322875	9.40E-01	3.632
890	3.43E+02	0.322239	9.24E-01	3.626
900	3.06E+02	0.321602	7.43E-01	3.62
910	2.72E+02	0.320964	6.25E-01	3.614
920	2.40E+02	0.320325	7.44E-01	3.608
930	2.10E+02	0.319684	4.32E-01	3.602
940	1.83E+02	0.31915	4.72E-01	3.597
950	1.57E+02	0.318615	1.47E-01	3.592
960	1.34E+02	0.318079	4.21E-01	3.587
970	1.14E+02	0.317543	6.35E-01	3.582
980	9.59E+01	0.317113	6.05E-01	3.578
990	7.92E+01	0.316683	7.32E-01	3.574
1000	6.40E+01	0.316252	7.35E-01	3.57
1010	5.11E+01	0.316252	7.19E-01	3.566
1020	3.99E+01	0.316252	6.99E-01	3.563
1030	3.02E+01	0.316252	6.91E-01	3.56
1040	2.26E+01	0.316252	6.72E-01	3.557
1050	1.63E+01	0.316252	6.55E-01	3.554
1060	1.11E+01	0.316252	6.36E-01	3.551
1070	8.00E+00	0.316252	6.05E-01	3.548
1080	6.20E+00	0.316252	5.97E-01	3.546
1090	4.70E+00	0.316252	5.56E-01	3.544
1100	3.50E+00	0.316252	4.86E-01	3.541
1110	2.70E+00	0.316252	4.79E-01	3.539
1120	2.00E+00	0.316252	1.42E-01	3.537
1130	1.50E+00	0.316252	7.06E-02	3.534
1140	1.00E+00	0.316252	2.56E-01	3.532
1150	6.80E-01	0.316252	1.22E-01	3.53
1160	4.20E-01	0.316252	2.86E-01	3.528
1170	2.20E-01	0.316252	4.59E-01	3.526
1180	6.50E-02	0.316252	4.41E-01	3.524
1190	3.60E-02	0.316252	4.62E-01	3.522
1200	2.20E-02	0.316252	4.48E-01	3.52

APPENDIX-B

B.1 Module 1

```
      clear
%*********thickness of the cell in micron***********
%disp(thickness);
syms V;
thickness=400E-6;
t=thickness*1E2;
p=((t/1E-4)-1)+9+1;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
n=0;
m=zeros([1200 1]);
dummy=zeros([1200 p]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%R=zeros([92 1]);
theta=zeros([92 1]);
n0=1;
n_si=3.8;
lam0=600;
lm=load('wavelength_nm_1200.txt');
n1=sqrt(n_si);
r1=((n0-n1)/(n0+n1));
r2=((n1-n_si)/(n1+n_si));
%***Thickness of the ARC layer in (nm)*****************
D1=lam0/(4*n1);
%***************************************
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   grid
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
S=(100E-4):(100E-4):(5000E-4);
Ro_e=40;
Plost_e=ones([p 50]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
J_short_ckt=zeros([1 7]);
J_short_ckt1=zeros([1 7]);
J_short_ckt2=zeros([1 7]);
J_short_ckt3=zeros([1 7]);
efficy=zeros([1 7]);
efficy1=zeros([1 7]);
efficy2=zeros([1 7]);
efficy3=zeros([1 7]);
fil_fac=zeros([1 7]);
fil_fac1=zeros([1 7]);
fil_fac2=zeros([1 7]);
fil_fac3=zeros([1 7]);
open_ckt_V=zeros([1 7]);
open_ckt_V1=zeros([1 7]);
open_ckt_V2=zeros([1 7]);
open_ckt_V3=zeros([1 7]);
I0_ckt=zeros([1 7]);
I0_ckt1=zeros([1 7]);
I0_ckt2=zeros([1 7]);
I0_ckt3=zeros([1 7]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Area=1;
```

```
flux_initial=zeros([92 1]);
J_scP=zeros([92 1]);
J_scP_1=zeros([92 1]);
J_scP_2=zeros([92 1]);
J_scP_3=zeros([92 1]);
J_scP_4=zeros([92 1]);
J_scN=zeros([92 1]);
J_scN_1=zeros([92 1]);
J_scN_2=zeros([92 1]);
J_scN_3=zeros([92 1]);
J_scN_4=zeros([92 1]);
J_dr=zeros([92 1]);
J_sc1=zeros([92 p]);
J_scfix_w1=zeros([92 1]);
Jdark_P1=zeros([92 1]);
Jdark_N1=zeros([92 1]);
Jdark1=zeros([92 p]);
%J1=zeros([1 p]);
Jdark=zeros([1 p]);
J3=zeros([1 p]);
I_series=zeros([1 p]);
%J_sc2=zeros([92 p]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
V_oc=zeros([1 p]);
QE_P=zeros([92 0]);
QE_N=zeros([92 0]);
QE1=zeros([92 p]);
QE=zeros([92 1]);
SR=zeros([92 1]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
I=zeros([1 p]);
Idark=zeros([1 p]);
 V_m=zeros([1 p]);
 I_m=zeros([1 p]);
 P=zeros([1200 1]);
 Pmax=zeros([1 p]);
 FF=zeros([1 p]);
 efficiency=zeros([1 p]);
 %%%%% G is irradiance in(W/m2)%%%%%%
 G=1000;
 q=1.6E-19;
 K=1.381E-23;
 T=300;
 V_t=K*T/q;
b=1;
base_doping=[1E15 1E16 1E17 1E18];
emitter_doping=[1E15 1E16 1E17 1E18 1E19 1E20 1E21];
for pr=1:1:4
  for qr=1:1:7
Na=base_doping(1,pr);
Nd=emitter_doping(1,qr);
Na_plus=1E19;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Up=130+(370/(1+((Nd/8E17)^1.25)));
Tp=1/(((7.8E-13)*Nd)+((1.7E-31)*Nd*Nd));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Un=232+(1180/((1+(Na/8E16)^0.9)));
Tn=1/(((3.45E-12)*Na)+((0.95E-31)*Na*Na));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Un_plus=232+(1180/((1+(Na_plus/8E16)^0.9)));
Tn_plus=1/(((3.45E-12)*Na_plus)+((0.95E-31)*Na_plus*Na_plus));
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
D_p=Up*(K*T/q);

%*************cm^2/sec*******************
D_n=Un*(K*T/q);

%%%%%%%%%%%%%%%%%%%%%%%%%%%
Dn_plus=Un_plus*(K*T/q);

%************cm****************
L_p=((Tp*D_p)^0.5);

%************cm****************
L_n=((Tn*D_n)^0.5);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ln_plus=((Tn_plus*Dn_plus)^0.5);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
alpha=load('abs_coeff_cm.txt');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ni=1E10;
%*******micron***********
lamda=lm*1E-3;

%**********watt/(m^2-um)*************************
spectral_irradiance=load('irradiance_wm2_nm_92.txt')*1000;

%**************unitless************
R=load('reflection_coeff_1200.txt');
%
%**********microns***************
%x=load('thickness.txt');
x=load('thk_400_1.txt');
thk=x*1E2;
%********Vo built in voltage*********
Vo=V_t*log(Na*Nd/(Ni*Ni));

%********W junction width in cm*************
W=sqrt(((2*12*8.8542E-12*Vo)/q)*((Na+Nd)/(Na*Nd)));
Xp=W*(Nd/(Na+Nd));
Xn=W*(Na/(Na+Nd));

%********W_n thickness of N region in cm*************
W_n=x*1E2;

%********Wp_plus thickness in cm*************
W_P_plus=0.1E-4:0.1E-4:50E-4;

%**********cm/sec************
%S_n=100;
S_back=zeros([1 500]);
for tr=1:1:500;
S_back(1,tr)=(((Na/Na_plus)*(Dn_plus/Ln_plus))*coth(W_P_plus(1,tr)/Ln_plus)
);
end
if ((Na==1E15)&&(Na_plus==1E19))
S_n=1.678;
Wp_plus=165E-5;
elseif((Na==1E16)&&(Na_plus==1E19))
```

```
S_n=16.78;
Wp_plus=165E-5;
elseif((Na==1E17)&&(Na_plus==1E19))
S_n=167.8;
Wp_plus=165E-5;
elseif((Na==1E18)&&(Na_plus==1E19))
S_n=1678;
Wp_plus=165E-5;
else
S_n=(((Na*Dn_plus)/(Na_plus*Ln_plus))*coth(Wp_plus/Ln_plus));
Wp_plus=5E-4;
end
figure(1)
plot(W_P_plus,S_back);
xlabel('thickness(cm)');
ylabel('surface recombination velocity(cm/sec)');
title('recombination velocity at P/P+ interface');
datacursormode on
%**********cm/sec************
S_p=2E5;
%**********cm^2/sec************
%********cm*************
W_p=(ones([p 1])*t)-(W_n+(ones([p 1])*W)+(ones([p 1])*Wp_plus));

   for j=1:1:11;


             for a=1:1:92;


%%%%%%%%%%%%%%%%%%%photon flux at the surface%%%%%%%%%%%%%%%%%%%%
flux_initial(a,1)=spectral_irradiance(a,1)*lamda(a,1)*(1E16/19.8);
%%%%%%%%%%%%EMITTER SHORT CIRCUIT SPECTRAL CURRENT
DENSITY%%%%%%%%%%%%%%%%%%%
%*******************(Amp/cm^2um)*************************************
%J_scE(a,1)={{(q*alpha(a,1)*flux_initial(a,1)*(1-
R(a,1))*L_p(b,1))/((alpha(a,1)*L_p(b,1))+1)}*{1/((alpha(a,1)*L_p(b,1))-
1)}}*{{-alpha(a,1)*L_p(b,1)*exp(-
alpha(a,1)*W_n(j,1))}+({S_n*L_p(b,1)/D_p(b,1)}+{alpha(a,1)*L_p(b,1)}-{exp(-
alpha(a,1)*W_n(j,1))*(({S_n*L_p(b,1)/D_p(b,1)}*cosh(W_n(j,1)/L_p(b,1)))+sin
h(W_n(j,1)/L_p(b,1)))})/(cosh(W_n(j,1)/L_p(b,1))+({S_n*L_p(b,1)/D_p(b,1)}*s
inh(W_n(j,1)/L_p(b,1))))};
J_scP(a,1)=(((q*alpha(a,1)*flux_initial(a,1)*(1-
R(a,1))*L_p(b,1))/((alpha(a,1)*L_p(b,1))+1))*(1/((alpha(a,1)*L_p(b,1))-
1)))*((-alpha(a,1)*L_p(b,1)*exp(-
alpha(a,1)*W_n(j,1)))+((S_p*L_p(b,1)/D_p(b,1))+(alpha(a,1)*L_p(b,1))-(exp(-
alpha(a,1)*W_n(j,1))*(((S_p*L_p(b,1)/D_p(b,1))*cosh(W_n(j,1)/L_p(b,1)))+sin
h(W_n(j,1)/L_p(b,1)))))/(cosh(W_n(j,1)/L_p(b,1))+((S_p*L_p(b,1)/D_p(b,1))*s
inh(W_n(j,1)/L_p(b,1)))));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%


Jdark_P1(a,1)=(q*Ni*Ni*D_p(b,1)/(Nd*L_p(b,1)))*((S_p*(L_p(b,1)/D_p(b,1))*co
sh(W_n(j,1)/L_p(b,1))+sinh(W_n(j,1)/L_p(b,1)))/(S_p*(L_p(b,1)/D_p(b,1))*sin
h(W_n(j,1)/L_p(b,1))+cosh(W_n(j,1)/L_p(b,1))));

%%%%%%%%%%%quantum efficiency of emitter %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%J_scB(a,1)={{(q*alpha(a,1)*{flux_initial(a,1)*exp(-
alpha(a,1)*W_n(j,1))}*(1-
```

```
R(a,1))*L_n(b,1))/((alpha(a,1)*L_n(b,1))+1)}*{1/((alpha(a,1)*L_n(b,1))-
1)}}*{{-alpha(a,1)*L_n(b,1)}-
({S_p*L_n(b,1)/D_n(b,1)}*{cosh(W_p(j,1)/L_n(b,1))-exp(-
alpha(a,1)*W_p(j,1))}+sinh(W_p(j,1)/L_n(b,1))+{alpha(a,1)*L_n(b,1)*exp(-
alpha(a,1)*W_p(j,1))})/(cosh(W_p(j,1)/L_n(b,1))+({S_p*L_n(b,1)/D_n(b,1)}*si
nh(W_p(j,1)/L_n(b,1)))))};
J_scN(a,1)=(((1.6E-19*alpha(a,1)*(flux_initial(a,1)*exp(-
alpha(a,1)*(W_n(j,1)+W)))*(1-
R(a,1))*L_n(b,1))/((alpha(a,1)*L_n(b,1))+1))*(1/((alpha(a,1)*L_n(b,1))-
1)))*((alpha(a,1)*L_n(b,1))-
((S_n*L_n(b,1)/D_n(b,1))*(cosh(W_p(j,1)/L_n(b,1))-exp(-
alpha(a,1)*W_p(j,1)))+sinh(W_p(j,1)/L_n(b,1))+(alpha(a,1)*L_n(b,1)*exp(-
alpha(a,1)*W_p(j,1))))/(cosh(W_p(j,1)/L_n(b,1))+((S_n*L_n(b,1)/D_n(b,1))*si
nh(W_p(j,1)/L_n(b,1)))));
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%
Jdark_N1(a,1)=(q*Ni*Ni*D_n(b,1)/(Na*L_n(b,1)))*((S_n*(L_n(b,1)/D_n(b,1))*co
sh(W_p(j,1)/L_n(b,1))+sinh(W_p(j,1)/L_n(b,1)))/(S_n*(L_n(b,1)/D_n(b,1))*sin
h(W_p(j,1)/L_n(b,1))+cosh(W_p(j,1)/L_n(b,1))));
%%%%%%%quantum efficiency of base%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%QE_N(a,1)=J_scN(a,1)/(q*flux_initial(a,1)*(1-R(a,1)));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
J_dr(a,1)=(q*flux_initial(a,1)*(1-R(a,1))*exp(-alpha(a,1)*W_n(j,1))*(1-
exp(-alpha(a,1)*W)));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
J_sc1(a,j)=J_scP(a,1)+J_scN(a,1)+J_dr(a,1);

 %%%%%%%%%%%%%dark current%%%%%%%%%%%%%%%%
 Jdark1(a,j)=(Jdark_P1(a,1)+Jdark_N1(a,1));
  %%%%%%%%%%%%total quantum effciency in percentage%%%%%%%%%%%%%%
 QE1(a,j)=J_sc1(a,j)/(q*flux_initial(a,1)*(1-R(a,1)));
 J_scfix_w1(a,1)=(J_sc1(a,j));
 QE(a,1)=QE1(a,j);
 SR(a,1)=QE1(a,j)*lamda(a,1)*0.808;

             end
             if(j==2)
            quantan_efficiency=QE;
            spectral_resp=SR;
   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
expr=pr;
figure(2)
if (Nd==1E15)

    switch (expr)
        case (1)
        subplot(2,2,1);plot(lm,quantan_efficiency);
        hold on
        case (2)
        subplot(2,2,1);plot(lm,quantan_efficiency,'r');
        hold on
        case (3)
        subplot(2,2,1);plot(lm,quantan_efficiency,'g');
        hold on
        otherwise
        subplot(2,2,1);plot(lm,quantan_efficiency,'m');
        hold off
        title('For Nd=1E15');
```

```
        xlabel('wavelength (nm)');
        ylabel('QE');
    end
end
if(Nd==1E16)
   switch(expr)
       case(1)
        subplot(2,2,2);plot(lm,quantan_efficiency);
        hold on
        case(2)
        subplot(2,2,2);plot(lm,quantan_efficiency,'r');
        hold on
        case(3)
        subplot(2,2,2);plot(lm,quantan_efficiency,'g');
        hold on
       otherwise
        subplot(2,2,2);plot(lm,quantan_efficiency,'m');
        hold off
        title('For Nd=1E16');
        xlabel('wavelength (nm)');
        ylabel('QE');
   end
end
if(Nd==1E17)
    switch(expr)
        case(1)
        subplot(2,2,3);plot(lm,quantan_efficiency);
        hold on
        case(2)
        subplot(2,2,3);plot(lm,quantan_efficiency,'r');
        hold on
        case(3)
        subplot(2,2,3);plot(lm,quantan_efficiency,'g');
        hold on
        otherwise
        subplot(2,2,3);plot(lm,quantan_efficiency,'m');
        hold off
        title('For Nd=1E17');
        xlabel('wavelength (nm)');
        ylabel('QE');
    end
end
if(Nd==1E18)
    switch(expr)
        case(1)
        subplot(2,2,4);plot(lm,quantan_efficiency);
        hold on
        case(2)
        subplot(2,2,4);plot(lm,quantan_efficiency,'r');
        hold on
        case(3)
        subplot(2,2,4);plot(lm,quantan_efficiency,'g');
        hold on
        otherwise
        subplot(2,2,4);plot(lm,quantan_efficiency,'m');
        hold off
        title('For Nd=1E18');
        xlabel('wavelength (nm)');
        ylabel('QE');
        suptitle('variation of QE with wavelength keeping a constant
junction depth=0.1um');
```

```
    end
end
figure(3)
if(Nd==1E19)
    switch(expr)
        case(1)
        subplot(2,2,1);plot(lm,quantan_efficiency);
        hold on
        case(2)
        subplot(2,2,1);plot(lm,quantan_efficiency,'r');
        hold on
        case(3)
        subplot(2,2,1);plot(lm,quantan_efficiency,'g');
        hold on
        otherwise
        subplot(2,2,1);plot(lm,quantan_efficiency,'m');
        hold off
        title('For Nd=1E19');
        xlabel('wavelength (nm)');
        ylabel('QE');
    end
end
if(Nd==1E20)
    switch(expr)
        case(1)
        subplot(2,2,2);plot(lm,quantan_efficiency);
        hold on
        case(2)
        subplot(2,2,2);plot(lm,quantan_efficiency,'r');
        hold on
        case(3)
        subplot(2,2,2);plot(lm,quantan_efficiency,'g');
        hold on
        otherwise
        subplot(2,2,2);plot(lm,quantan_efficiency,'m');
        hold off
        title('For Nd=1E20');
        xlabel('wavelength (nm)');
        ylabel('QE');
    end
end
if(Nd==1E21)
    switch(expr)
        case(1)
        subplot(2,2,3);plot(lm,quantan_efficiency);
        hold on
        case(2)
        subplot(2,2,3);plot(lm,quantan_efficiency,'r');
        hold on
        case(3)
        subplot(2,2,3);plot(lm,quantan_efficiency,'g');
        hold on
        otherwise
        subplot(2,2,3);plot(lm,quantan_efficiency,'m');
        hold off
        title('For Nd=1E21');
        xlabel('wavelength (nm)');
        ylabel('QE');
        suptitle('variation of QE with wavelength keeping a constant 
junction depth=0.1um');
    end
```

```
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(5)
if (Nd==1E15)

    switch (expr)
        case (1)
        subplot(2,2,1);plot(lm,spectral_resp);
        hold on
        case (2)
        subplot(2,2,1);plot(lm,spectral_resp,'r');
        hold on
        case (3)
        subplot(2,2,1);plot(lm,spectral_resp,'g');
        hold on
        otherwise
        subplot(2,2,1);plot(lm,spectral_resp,'m');
        hold off
        title('For Nd=1E15');
        xlabel('wavelength (nm)');
        ylabel('SR');
    end
end
if(Nd==1E16)
   switch(expr)
       case(1)
        subplot(2,2,2);plot(lm,spectral_resp);
        hold on
        case(2)
        subplot(2,2,2);plot(lm,spectral_resp,'r');
        hold on
        case(3)
        subplot(2,2,2);plot(lm,spectral_resp,'g');
        hold on
       otherwise
        subplot(2,2,2);plot(lm,spectral_resp,'m');
        hold off
        title('For Nd=1E16');
        xlabel('wavelength (nm)');
        ylabel('SR');
   end
end
if(Nd==1E17)
    switch(expr)
        case(1)
        subplot(2,2,3);plot(lm,spectral_resp);
        hold on
        case(2)
        subplot(2,2,3);plot(lm,spectral_resp,'r');
        hold on
        case(3)
        subplot(2,2,3);plot(lm,spectral_resp,'g');
        hold on
        otherwise
        subplot(2,2,3);plot(lm,spectral_resp,'m');
        hold off
        title('For Nd=1E17');
        xlabel('wavelength (nm)');
        ylabel('SR');
    end
end
```

```
if(Nd==1E18)
    switch(expr)
        case(1)
        subplot(2,2,4);plot(lm,spectral_resp);
        hold on
        case(2)
        subplot(2,2,4);plot(lm,spectral_resp,'r');
        hold on
        case(3)
        subplot(2,2,4);plot(lm,spectral_resp,'g');
        hold on
        otherwise
        subplot(2,2,4);plot(lm,spectral_resp,'m');
        hold off
        title('For Nd=1E18');
        xlabel('wavelength (nm)');
        ylabel('SR');
        suptitle('variation of SR with wavelength keeping a constant
junction depth=0.1um');
    end
end
figure(6)
if(Nd==1E19)
    switch(expr)
        case(1)
        subplot(2,2,1);plot(lm,spectral_resp);
        hold on
        case(2)
        subplot(2,2,1);plot(lm,spectral_resp,'r');
        hold on
        case(3)
        subplot(2,2,1);plot(lm,spectral_resp,'g');
        hold on
        otherwise
        subplot(2,2,1);plot(lm,spectral_resp,'m');
        hold off
        title('For Nd=1E19');
        xlabel('wavelength (nm)');
        ylabel('SR');
    end
end
if(Nd==1E20)
    switch(expr)
        case(1)
        subplot(2,2,2);plot(lm,spectral_resp);
        hold on
        case(2)
        subplot(2,2,2);plot(lm,spectral_resp,'r');
        hold on
        case(3)
        subplot(2,2,2);plot(lm,spectral_resp,'g');
        hold on
        otherwise
        subplot(2,2,2);plot(lm,spectral_resp,'m');
        hold off
        title('For Nd=1E20');
        xlabel('wavelength (nm)');
        ylabel('SR');
    end
end
if(Nd==1E21)
```

```
    switch(expr)
        case(1)
        subplot(2,2,3);plot(lm,spectral_resp);
        hold on
        case(2)
        subplot(2,2,3);plot(lm,spectral_resp,'r');
        hold on
        case(3)
        subplot(2,2,3);plot(lm,spectral_resp,'g');
        hold on
        otherwise
        subplot(2,2,3);plot(lm,spectral_resp,'m');
        hold off
        title('For Nd=1E21');
        xlabel('wavelength (nm)');
        ylabel('SR');
        suptitle('variation of SR with wavelength keeping a constant 
junction depth=0.1um');
    end
end
             end

  end
   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
     J_sc=sum(J_sc1);
     if (Na==1E15)
        J_short_ckt(1,qr)=J_sc(1,2);
     elseif(Na==1E16)
         J_short_ckt1(1,qr)=J_sc(1,2);
     elseif(Na==1E17)
         J_short_ckt2(1,qr)=J_sc(1,2);
     elseif(Na==1E18)
         J_short_ckt3(1,qr)=J_sc(1,2);
     end
     if ((Na==1E15)&&(Nd==1E20))
         Jsc_width=[J_sc(1,1) J_sc(1,2) J_sc(1,3) J_sc(1,4) J_sc(1,5) 
J_sc(1,6) J_sc(1,7) J_sc(1,8) J_sc(1,9) J_sc(1,10) J_sc(1,11)];
     end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
     J_1=(J_sc1');
     J_2=sum(J_1);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
     J1=sum(Jdark1);
     J2=(exp(V/V_t)-1)*J1;
      I_l=Area*J_sc;
      I0=Area*J1;
      %%%%%%%%%%%%%%%%%%%%%%%%%%%
      if (Na==1E15)
        I0_ckt(1,qr)=I0(1,2);
     elseif(Na==1E16)
         I0_ckt1(1,qr)=I0(1,2);
     elseif(Na==1E17)
         I0_ckt2(1,qr)=I0(1,2);
     elseif(Na==1E18)
         I0_ckt3(1,qr)=I0(1,2);
     end
     if ((Na==1E15)&&(Nd==1E20))
         I0_width=[I0(1,1) I0(1,2) I0(1,3) I0(1,4) I0(1,5) I0(1,6) I0(1,7) 
I0(1,8) I0(1,9) I0(1,10) I0(1,11)];
     end
      %%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
      Idark=zeros([1 11]);
      I=zeros([1 11]);
      P=zeros([1200 1]);
      Pmax=zeros([1 11]);
       for k=1:1:p;
           n=0;
           V_oc(1,k)=V_t*log(1+(J_sc(1,k)/J1(1,k)));
             if
((k==1)||(k==2)||(k==3)||(k==4)||(k==5)||(k==6)||(k==7)||(k==8)||(k==9)||(k
==10)||(k==11))
            for volt=-0.5:0.001:V_oc(1,k);

         n=n+1;
      m(n,1)=volt;
      Jdark(1,k)=(exp(volt/V_t)-1)*J1(1,k);
      dummy(n,k)=Jdark(1,k);
      J3(1,k)=J_sc(1,k)-Jdark(1,k);

      %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
      %         power                         %
      %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
      Idark(1,k)=(exp(volt/V_t)-1)*I0(1,k);
      I(1,k)=I_l(1,k)-Idark(1,k);

      if(volt>=0)
   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
      P(n,1)=volt*abs(I(1,k));

       end
      Pmax(1,k)=max(P);
            end
            n=0;
           for volt=-0.5:0.001:V_oc(1,k);
            n=n+1;
            Idark(1,k)=(exp(volt/V_t)-1)*I0(1,k);
            I(1,k)=I_l(1,k)-Idark(1,k);
            cond=Pmax(1,k)-(volt*I(1,k));
             if(cond==0)
             V_m(1,k)=volt;
             I_m(1,k)=I(1,k);
             FF(1,k)=((V_m(1,k)*I_m(1,k))/(V_oc(1,k)*I_l(1,k)));
             efficiency(1,k)=(FF(1,k)*V_oc(1,k)*J_sc(1,k)/(G/10000));
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
             end
           end
             end
       end
     if (Na==1E15)
        efficy(1,qr)=efficiency(1,2);
        fil_fac(1,qr)=FF(1,2);
        open_ckt_V(1,qr)=V_oc(1,2);
     elseif(Na==1E16)
         efficy1(1,qr)=efficiency(1,2);
         fil_fac1(1,qr)=FF(1,2);
         open_ckt_V1(1,qr)=V_oc(1,2);
     elseif(Na==1E17)
         efficy2(1,qr)=efficiency(1,2);
         fil_fac2(1,qr)=FF(1,1);
         open_ckt_V2(1,qr)=V_oc(1,2);
```

```
     elseif(Na==1E18)
         efficy3(1,qr)=efficiency(1,2);
         fil_fac3(1,qr)=FF(1,2);
         open_ckt_V3(1,qr)=V_oc(1,2);
     end
     if ((Na==1E15)&&(Nd==1E20))
         efficiency_width=[efficiency(1,1) efficiency(1,2) efficiency(1,3)
efficiency(1,4) efficiency(1,5) efficiency(1,6) efficiency(1,7)
efficiency(1,8) efficiency(1,9) efficiency(1,10) efficiency(1,11)];
         FF_width=[FF(1,1) FF(1,2) FF(1,3) FF(1,4) FF(1,5) FF(1,6) FF(1,7)
FF(1,8) FF(1,9) FF(1,10) FF(1,11)];
         V_oc_width=[V_oc(1,1) V_oc(1,2) V_oc(1,3) V_oc(1,4) V_oc(1,5)
V_oc(1,6) V_oc(1,7) V_oc(1,8) V_oc(1,9) V_oc(1,10) V_oc(1,11)];
     end
 end
end
figure(7)
semilogx(emitter_doping,J_short_ckt);
hold on
semilogx(emitter_doping,J_short_ckt1,'r');
hold on
semilogx(emitter_doping,J_short_ckt2,'g');
hold on
semilogx(emitter_doping,J_short_ckt3,'m');
title('variation in Jsc with junction depth keeping doping constant');
Xlabel('junction depth (um)');
ylabel('Jsc (A/cm2)');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(8)
loglog(emitter_doping,I0_ckt);
hold on
loglog(emitter_doping,I0_ckt1,'r');
hold on
loglog(emitter_doping,I0_ckt2,'g');
hold on
loglog(emitter_doping,I0_ckt3,'m');
title('variation in J0 with junction depth keeping doping constant');
Xlabel('junction depth (um)');
ylabel('J0 (A/cm2)');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(9)
semilogx(emitter_doping,efficy);
hold on
semilogx(emitter_doping,efficy1,'r');
hold on
semilogx(emitter_doping,efficy2,'g');
hold on
semilogx(emitter_doping,efficy3,'m');
title('variation in efficiency with junction depth keeping doping
constant');
Xlabel('junction depth (um)');
ylabel('efficiency (%)');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(10)
semilogx(emitter_doping,fil_fac);
hold on
semilogx(emitter_doping,fil_fac1,'r');
hold on
semilogx(emitter_doping,fil_fac2,'g');
hold on
semilogx(emitter_doping,fil_fac3,'m');
```

```
title('variation in fill factor with junction depth keeping doping
constant');
Xlabel('junction depth (um)');
ylabel('FF');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(11)
semilogx(emitter_doping,open_ckt_V);
hold on
semilogx(emitter_doping,open_ckt_V1,'r');
hold on
semilogx(emitter_doping,open_ckt_V2,'g');
hold on
semilogx(emitter_doping,open_ckt_V3,'m');
title('variation in Voc with junction depth keeping doping constant');
Xlabel('junction depth (um)');
ylabel('Voc (volts)');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
junction_depth=[0.05 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1];
figure(12)
plot(junction_depth,Jsc_width);
title('variation in Jsc with junction depth keeping doping constant');
Xlabel('junction depth (um)');
ylabel('Jsc (A/cm2)');
%%%%%%%%%%%%%%%%%%%%%%%%
figure(13)
semilogy(junction_depth,I0_width);
axis([0 1 1E-11 1E-9 ]);
title('variation in J0 with junction depth keeping doping constant');
Xlabel('junction depth (um)');
ylabel('J0 (A/cm2)');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(14)
plot(junction_depth,V_oc_width);
title('variation in Voc with junction depth keeping doping constant');
Xlabel('junction depth (um)');
ylabel('Voc (volts)');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(15)
plot(junction_depth,FF_width);
title('variation in FF with junction depth keeping doping constant');
Xlabel('junction depth (um)');
ylabel('FF');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(16)
plot(junction_depth,efficiency_width);
title('variation in efficiency with junction depth keeping doping
constant');
Xlabel('junction depth (um)');
ylabel('efficiency (%)');
```

B.2 Module 2

```
clear
%*********thickness of the cell in micron***********
%disp(thickness);
syms V;
thickness=400E-6;
t=thickness*1E2;
p=((t/1E-4)-1)+9+1;
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
n=0;
m=zeros([1200 1]);
dummy=zeros([1200 p]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
R=zeros([92 1]);
theta=zeros([92 1]);
n0=1;
n_si=3.8;
lam0=600;
lm=load('wavelength_nm_1200.txt');
n1=sqrt(n_si);
r1=((n0-n1)/(n0+n1));
r2=((n1-n_si)/(n1+n_si));
%***Thickness of the ARC layer in (nm)*****************
D1=lam0/(4*n1);
%***************************************
for a=1:1:92;
theta(a,1)=((2*pi*n1*D1)/lm(a,1));
R(a,1)=(((r1*r1)+(r2*r2)+2*r1*r2*cos(2*theta(a,1)))/(1+(r1*r1*r2*r2)+(2*r1*
r2*cos(2*theta(a,1)))));
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%texturing
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
alpha=load('abs_coeff_cm.txt');
lamb_R=0.97/2;
face_theta=70.53/2;
frac=zeros([92 1]);
text_beta=zeros([92 1]);
alpha_eff=zeros([92 1]);
abs_length=zeros([92 1]);
mu=load('rif_indx_92.txt');
for tcc=1:1:92;
frac(tcc,1)=(1/(mu(tcc,1)*mu(tcc,1)));
text_beta(tcc,1)=acosd((cosd(face_theta)/mu(tcc,1)))-face_theta;
alpha_eff(tcc,1)=((alpha(tcc,1)/cosd(text_beta(tcc,1)))+((1/t)*log((1-
(lamb_R*(1-frac(tcc,1))*exp(-4*alpha(tcc,1)*t)))/(1-(lamb_R*(1-
(frac(tcc,1)*exp(-2*alpha(tcc,1)*t))))))));
abs_length(tcc,1)=(1/alpha_eff(tcc,1));
end
figure(1);
semilogy(lm,alpha);
hold on
semilogy(lm,alpha_eff,'-r');
xlabel('wavelength(nm)');
ylabel('absorption coefficient(1/cm)');
title('absorption coefficient with wavelength');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%5
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   grid
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%R_series=[0.5;5];
S=(100E-4):(100E-4):(5000E-4);
Ro_e=40;
Plost_e=ones([p 50]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Area=1;
flux_initial=zeros([92 1]);
J_scP=zeros([92 1]);
```

```
J_scP_1=zeros([92 1]);
J_scP_2=zeros([92 1]);
J_scP_3=zeros([92 1]);
J_scP_4=zeros([92 1]);
J_scN=zeros([92 1]);
J_scN_1=zeros([92 1]);
J_scN_2=zeros([92 1]);
J_scN_3=zeros([92 1]);
J_scN_4=zeros([92 1]);
J_dr=zeros([92 1]);
J_sc1=zeros([92 p]);
J_scfix_w1=zeros([92 1]);
Jdark_P1=zeros([92 1]);
Jdark_N1=zeros([92 1]);
Jdark1=zeros([92 p]);
%J1=zeros([1 p]);
Jdark=zeros([1 p]);
J3=zeros([1 p]);
I_series=zeros([1 p]);
%J_sc2=zeros([92 p]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
V_oc=zeros([1 p]);
QE_P=zeros([92 0]);
QE_N=zeros([92 0]);
QE1=zeros([92 p]);
QE=zeros([92 1]);
SR=zeros([92 1]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
I=zeros([1 p]);
Idark=zeros([1 p]);
 V_m=zeros([1 p]);
 I_m=zeros([1 p]);
 P=zeros([1200 1]);
 Pmax=zeros([1 p]);
 FF=zeros([1 p]);
 efficiency=zeros([1 p]);
 %%%%% G is irradiance in(W/m2)%%%%%%
 G=1000;
 q=1.6E-19;
 K=1.381E-23;
 T=300;
 V_t=K*T/q;

b=1;

Na=1E15;       %load('acceptor_concentration.txt');
Nd=1E20;        %load('donar_concentration.txt');
Na_plus=1E19;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Up=130+(370/(1+((Nd/8E17)^1.25)));
Tp=1/(((7.8E-13)*Nd)+((1.7E-31)*Nd*Nd));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Un=232+(1180/((1+(Na/8E16)^0.9)));
Tn=1/(((3.45E-12)*Na)+((0.95E-31)*Na*Na));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Un_plus=232+(1180/((1+(Na_plus/8E16)^0.9)));
Tn_plus=1/(((3.45E-12)*Na_plus)+((0.95E-31)*Na_plus*Na_plus));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%D_p=3.3898;        %load('diff_coeff_ptype.txt');
D_p=Up*(K*T/q);
```

```
%*************cm^2/sec******************
%D_n=35.989;         %load('diff_coeff_ntype.txt');
D_n=Un*(K*T/q);

%%%%%%%%%%%%%%%%%%%%%%%%%%%
Dn_plus=Un_plus*(K*T/q);

%************cm***************
%L_p=4.366E-5;      %load('Diffusion_Length_hole.txt');
L_p=((Tp*D_p)^0.5);

%************cm***************
%L_n=10.2125E-02;   %load('Diffusion_Length_electron.txt');
L_n=((Tn*D_n)^0.5);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ln_plus=((Tn_plus*Dn_plus)^0.5);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ni=1E10;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%lm=load('wavelength_nm_1200.txt');
%*******micron***********
lamda=lm*1E-3;

%**********watt/(m^2-um)************************
spectral_irradiance=load('irradiance_wm2_nm_92.txt')*1000;

%**************unitless************
%R=load('reflection_coeff_1200.txt');
%
%**********microns**************
%x=load('thickness.txt');
x=load('thk_400.txt');
thk=x*1E2;
%********Vo built in voltage********
Vo=V_t*log(Na*Nd/(Ni*Ni));

%********W junction width in cm*************
W=sqrt(((2*12*8.8542E-12*Vo)/q)*((Na+Nd)/(Na*Nd)));
Xp=W*(Nd/(Na+Nd));
Xn=W*(Na/(Na+Nd));

%********W_n thickness of N region in cm************
W_n=x*1E2;

%********Wp_plus thickness in cm*************
W_P_plus=0.1E-4:0.1E-4:50E-4;

%**********cm/sec************
%S_n=100;
S_back=zeros([1 500]);
for tr=1:1:500;
S_back(1,tr)=(((Na*Dn_plus)/(Na_plus*Ln_plus))*coth(W_P_plus(1,tr)/Ln_plus)
);
end
%S_n=min(S_back);
S_n=1.678;%16.78;
```

```
Wp_plus=165E-5;%3.4E-4;%10E-4;%17E-4;
for tr=1:1:499;
    tr1=S_back(1,tr)-S_back(1,(tr+1));
    if(tr1<=0.001)
Wp_plus=W_P_plus(1,tr);
break;
    end
end

S_p=(1E-16)*Nd; %3E4;
%**********cm^2/sec************
%********cm*************
W_p=(ones([p 1])*t)-(W_n+(ones([p 1])*W)+(ones([p 1])*Wp_plus));

   for j=1:1:p;


             for a=1:1:92;


%%%%%%%%%%%%%%%%%%%photon flux at the surface%%%%%%%%%%%%%%%%%%%%
flux_initial(a,1)=spectral_irradiance(a,1)*lamda(a,1)*(1E16/19.8);
%%%%%%%%%%%%EMITTER SHORT CIRCUIT SPECTRAL CURRENT
DENSITY%%%%%%%%%%%%%%%%%%%
%*******************(Amp/cm^2um)*************************************
%J_scE(a,1)={{(q*alpha(a,1)*flux_initial(a,1)*(1-
R(a,1))*L_p(b,1))/((alpha(a,1)*L_p(b,1))+1)}*{1/((alpha(a,1)*L_p(b,1))-
1)}}*{{-alpha(a,1)*L_p(b,1)*exp(-
alpha(a,1)*W_n(j,1))}+({S_n*L_p(b,1)/D_p(b,1)}+{alpha(a,1)*L_p(b,1)}-{exp(-
alpha(a,1)*W_n(j,1))*(({S_n*L_p(b,1)/D_p(b,1)}*cosh(W_n(j,1)/L_p(b,1)))+sin
h(W_n(j,1)/L_p(b,1)))})/(cosh(W_n(j,1)/L_p(b,1))+({S_n*L_p(b,1)/D_p(b,1)}*s
inh(W_n(j,1)/L_p(b,1)))))};
J_scP(a,1)=(((q*alpha_eff(a,1)*flux_initial(a,1)*(1-
R(a,1))*L_p(b,1))/((alpha_eff(a,1)*L_p(b,1))+1))*(1/((alpha_eff(a,1)*L_p(b,
1))-1)))*((-alpha_eff(a,1)*L_p(b,1)*exp(-
alpha_eff(a,1)*W_n(j,1)))+((S_p*L_p(b,1)/D_p(b,1))+(alpha_eff(a,1)*L_p(b,1)
)-(exp(-
alpha_eff(a,1)*W_n(j,1))*(((S_p*L_p(b,1)/D_p(b,1))*cosh(W_n(j,1)/L_p(b,1)))
+sinh(W_n(j,1)/L_p(b,1)))))/(cosh(W_n(j,1)/L_p(b,1))+((S_p*L_p(b,1)/D_p(b,1
))*sinh(W_n(j,1)/L_p(b,1)))));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%

Jdark_P1(a,1)=(q*Ni*Ni*D_p(b,1)/(Nd*L_p(b,1)))*((S_p*(L_p(b,1)/D_p(b,1))*co
sh(W_n(j,1)/L_p(b,1))+sinh(W_n(j,1)/L_p(b,1)))/(S_p*(L_p(b,1)/D_p(b,1))*sin
h(W_n(j,1)/L_p(b,1))+cosh(W_n(j,1)/L_p(b,1))));


% %%%%%%%%%%%BASE SHORT CIRCUIT SPECTRAL CURRENT
DENSITY%%%%%%%%%%%%%%%%%%%
% %*******************(Amp/cm^2um)*************************************
% %J_scB(a,1)={{(q*alpha(a,1)*{flux_initial(a,1)*exp(-
alpha(a,1)*W_n(j,1))}*(1-
R(a,1))*L_n(b,1))/((alpha(a,1)*L_n(b,1))+1)}*{1/((alpha(a,1)*L_n(b,1))-
1)}}*{{-alpha(a,1)*L_n(b,1)}-
({S_p*L_n(b,1)/D_n(b,1)}*{cosh(W_p(j,1)/L_n(b,1))-exp(-
alpha(a,1)*W_p(j,1))}+sinh(W_p(j,1)/L_n(b,1))+{alpha(a,1)*L_n(b,1)*exp(-
```

```
alpha(a,1)*W_p(j,1))})/(cosh(W_p(j,1)/L_n(b,1))+({S_p*L_n(b,1)/D_n(b,1)}*si
nh(W_p(j,1)/L_n(b,1)))))};
%J_scN(a,1)=(((1.6E-19*alpha(a,1)*(flux_initial(a,1)*exp(-
alpha(a,1)*(W_n(j,1)+W)))*(1-
R(a,1))*L_n(b,1))/((alpha(a,1)*L_n(b,1))+1))*(1/((alpha(a,1)*L_n(b,1))-
1)))*((alpha(a,1)*L_n(b,1))-
((S_n*L_n(b,1)/D_n(b,1))*(cosh(W_p(j,1)/L_n(b,1))-exp(-
alpha(a,1)*W_p(j,1)))+sinh(W_p(j,1)/L_n(b,1))+(alpha(a,1)*L_n(b,1)*exp(-
alpha(a,1)*W_p(j,1))))/(cosh(W_p(j,1)/L_n(b,1))+((S_n*L_n(b,1)/D_n(b,1))*si
nh(W_p(j,1)/L_n(b,1))))));
J_scN(a,1)=(((1.6E-19*alpha_eff(a,1)*(flux_initial(a,1)*exp(-
alpha_eff(a,1)*(W_n(j,1)+W)))*(1-
R(a,1))*L_n(b,1))/((alpha_eff(a,1)*L_n(b,1))+1))*(1/((alpha_eff(a,1)*L_n(b,
1))-1)))*((alpha_eff(a,1)*L_n(b,1))-
((S_n*L_n(b,1)/D_n(b,1))*(cosh(W_p(j,1)/L_n(b,1))-exp(-
alpha_eff(a,1)*W_p(j,1)))+sinh(W_p(j,1)/L_n(b,1))+(alpha_eff(a,1)*L_n(b,1)*
exp(-
alpha_eff(a,1)*W_p(j,1))))/(cosh(W_p(j,1)/L_n(b,1))+((S_n*L_n(b,1)/D_n(b,1)
)*sinh(W_p(j,1)/L_n(b,1))))));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%
Jdark_N1(a,1)=(q*Ni*Ni*D_n(b,1)/(Na*L_n(b,1)))*((S_n*(L_n(b,1)/D_n(b,1))*co
sh(W_p(j,1)/L_n(b,1))+sinh(W_p(j,1)/L_n(b,1)))/(S_n*(L_n(b,1)/D_n(b,1))*sin
h(W_p(j,1)/L_n(b,1))+cosh(W_p(j,1)/L_n(b,1))));
%%%%%%%quantum efficiency of base%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%QE_N(a,1)=J_scN(a,1)/(q*flux_initial(a,1)*(1-R(a,1)));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
J_dr(a,1)=(q*flux_initial(a,1)*(1-R(a,1))*exp(-alpha_eff(a,1)*W_n(j,1))*(1-
exp(-alpha_eff(a,1)*W)));
%J_dr(a,1)=(q*flux_initial(a,1)*(1-R(a,1))*exp(-alpha(a,1)*W_n(j,1))*(1-
exp(-alpha(a,1)*W)));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
J_sc1(a,j)=J_scP(a,1)+J_scN(a,1)+J_dr(a,1);

 %%%%%%%%%%%%%dark current%%%%%%%%%%%%%%%%
 Jdark1(a,j)=(Jdark_P1(a,1)+Jdark_N1(a,1));
  %%%%%%%%%%%%total quantum effciency in percentage%%%%%%%%%%%%%%
 %QE1(a,j)=(QE_P(a,1)+QE_N(a,1))*100;
 QE1(a,j)=J_sc1(a,j)/(q*flux_initial(a,1)*(1-R(a,1)));



 J_scfix_w1(a,1)=(J_sc1(a,j));
 QE(a,1)=QE1(a,j);
 SR(a,1)=QE1(a,j)*lamda(a,1)*0.808;



             end


     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            if((j==1))%||(j==2)||(j==3))
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        Jsc_resis=J_scP+J_scN+J_dr;
        figure(2);
        plot(lm,(J_scP+J_scN+J_dr));
        title('Jsc with different wavelengths for junction depth=0.05 um')
        xlabel('wavelength(nm)')
        ylabel('Jsc(A/cm2-um)')
```

```
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            figure(3);
           % plot(lm,(J_scN+J_scP+J_dr),'--r');
            plot(lm,J_scP);
            hold on
            plot(lm,J_scN,'--c');
            hold on
            plot(lm,J_dr,'-.r');
            hold on
            title('JscP, JscN, J_dr with different wavelengths for junction
depth=0.05 um')
            xlabel('wavelength(nm)')
            ylabel('Jsc(A/cm2-um)')

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

            figure(4);
            plot(lm,QE);
            title('quantum efficiency with different wavelengths for
junction depth=0.05 um')
            xlabel('wavelength(nm)')
            ylabel('quantum efficiency')


            figure(5);
            plot(lm,SR);
            title('spectral response with different wavelengths for
junction depth=0.05 um')
            xlabel('wavelength(nm)')
            ylabel('spectral response')


            end
 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
  end
     J_sc=sum(J_sc1);
     figure(9);
     plot(J_sc);
     xlabel('thickness of N-region(um)')
     ylabel('Jsc(A/cm2-um')
     title('Jsc for different widths of N-region')
       % axis([1 300 0 2]);
     %%%%%%%%%%%%%%%%%%%%%%%%%%%%
     J_1=(J_sc1');
     J_2=sum(J_1);
%       figure(9);
%       plot(J_2);
     %%%%%%%%%%%%%%%%%%%%%%%%%%%%
     J1=sum(Jdark1);
     %J2=J_sc-J1;
     J2=(exp(V/V_t)-1)*J1;
      I_l=Area*J_sc;
      I0=Area*J1;
       for k=1:1:p;
           n=0;
           V_oc(1,k)=V_t*log(1+(J_sc(1,k)/J1(1,k)));
             if
((k==1)||(k==2)||(k==3)||(k==4)||(k==5)||(k==6)||(k==7)||(k==9)||(k==10)||(
k==11))
```

```
            for volt=-0.5:0.001:V_oc(1,k);

         n=n+1;  %for knowing different jdark values for different voltages
      m(n,1)=volt;
%          if ((k==1)||(k==50))
      Jdark(1,k)=(exp(volt/V_t)-1)*J1(1,k);
      dummy(n,k)=Jdark(1,k);
      J3(1,k)=J_sc(1,k)-Jdark(1,k);

      if(k==1)
      figure(11);
      title('current density Vs voltege curve with fixed junction
depth=0.05 um')
      xlabel('voltage(volts)')
      ylabel('current density(A/cm2)')
      plot((volt),J3(1,k),'-.r');
     % grid on
      axis([0 0.7 0 5]);
      hold on
      end
      %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
      %         power                         %
      %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
      Idark(1,k)=(exp(volt/V_t)-1)*I0(1,k);
      I(1,k)=I_l(1,k)-Idark(1,k);
  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
      if(volt>=0)
   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
      P(n,1)=volt*abs(I(1,k));

            Pmax(1,k)=max(P);

      end

            end
            n=0;
           for volt=-0.5:0.001:V_oc(1,k);
            n=n+1;
            Idark(1,k)=(exp(volt/V_t)-1)*I0(1,k);
            I(1,k)=I_l(1,k)-Idark(1,k);
            cond=Pmax(1,k)-(volt*I(1,k));
             if(cond==0)
             V_m(1,k)=volt;
             I_m(1,k)=I(1,k);
             FF(1,k)=((V_m(1,k)*I_m(1,k))/(V_oc(1,k)*I_l(1,k)));
             efficiency(1,k)=(FF(1,k)*V_oc(1,k)*J_sc(1,k)/(G/10000));
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        for h=1:1:50
        Pls_e=Ro_e*S(1,h)*S(1,h)*I_m(1,k)/(12*V_m(1,k));

        if(Pls_e<=(0.04*Pmax(1,k)))
            Plost_e(k,h)=Pls_e;
            T1=min(Plost_e);
            T2=T1-Pls_e;
            if(T2==0)
                spacing=s(1,h);
                length_fing=((T1*24)/(I_m(1,k)*I_m(1,k)*Ro_e*(spacing^3)));
            end
```

```
        end
        end

             end

           end


             end

       end
figure(14);
plot(lm,(R*100))
set(gca,'XTick',280:100:1260);
xlabel('wavelength(nm)');
ylabel('Reflection(%)');
title('% of spectral reflectance from silicon surface');
```

B.3 Module 3

```
clear
syms V;
thickness=300E-6;
t=thickness*1E2;
uy=t-(15E-4);

Na=1E16;
Nd=1E20;
Na_plus=1E19;
pregion_thk=5E-4:1E-4:uy;
%%%%%%%%%%%%%%%%%%%
uy1=((uy-10E-4)/1E-4)+1;
effic_sl=zeros([uy1 1]);
ideal_effic_sl=zeros([uy1 1]);
 N_tkh=zeros([uy1 1]);
 P_plus_tkh=zeros([uy1 1]);
 ser_res=zeros([uy1 1]);
 for ed=1:1:uy1;
 Wp_plus=pregion_thk(1,ed);
%for thickness2.txt one is added
p=((t/1E-4)-Wp_plus)+9+1;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
por_maxm=zeros([p 1]);
Rrmmt=zeros([115 10]);
Plost_e_tst=zeros([p 50]);
pow_rec_tst=zeros([p 50]);
R_emitter=zeros([115 10]);
jum=0;
%%%%%%%%%%%%%%%%%%%%%%%%%
power_los1=zeros([1 p]);
power_los2=zeros([1 p]);
power_los3=zeros([1 p]);
power_los4=zeros([1 p]);
power_los5=zeros([1 p]);
Prf=zeros([1 p]);
Psf=zeros([1 p]);
Pcf=zeros([1 p]);
Ptl=zeros([1 p]);
```

```
Prb=zeros([1 p]);
Psb=zeros([1 p]);
tpr=zeros([1 p]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%
n=0;
m=zeros([1200 1]);
dummy=zeros([1200 p]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
R=zeros([92 1]);
theta=zeros([92 1]);
n0=1;
n_si=3.8;
lam0=600;
lm=load('wavelength_nm_1200.txt');
n1=sqrt(n_si);
r1=((n0-n1)/(n0+n1));
r2=((n1-n_si)/(n1+n_si));
%***Thickness of the ARC layer in (nm)*****************
D1=lam0/(4*n1);
%***************************************
for a=1:1:92;
theta(a,1)=((2*pi*n1*D1)/lm(a,1));
R(a,1)=(((r1*r1)+(r2*r2)+2*r1*r2*cos(2*theta(a,1)))/(1+(r1*r1*r2*r2)+(2*r1*
r2*cos(2*theta(a,1)))));
end
series_resistance2=zeros([1 p]);
busbar_width=zeros([1 p]);
finger_width=zeros([1 p]);
spacing_finger=zeros([1 p]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
W_fing=(1E-4):(1E-4):(1000E-4);
width_busbar=100E-4:100E-4:1000E-4;
plos_fig=20000*ones([1000 1]);
Ro_e=zeros([p 1]);

Ploss_e_per=zeros([p 50]);

%Ploss_e=zeros([1 50]);
Plost_e=zeros([1 50]);
Pls_e=([1 50]);
%S=zeros([1 50]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%
S=(10E-4):(10E-4):(5000E-4);
spc=zeros([1 500]);
R_base=zeros([1 p]);
spac=zeros([1 500]);
optm1=5000*ones([1 500]);
width_fing=zeros([1 500]);
spacing_fing=zeros([1 500]);
W_fing1=zeros([1 500]);
%spac1=zeros([1 500]);
intx=2000*zeros([1 500]);
%%%%%%%%%%%%%%%%%%%%%%%%
spacing=zeros([1 p]);
length=1;
B=0.25;
Ro_smb=1.59E-6;%0.00188;
Ro_smf=1.59E-6;%0.00357;
Ro_c=370E-6;
M=3;
W_finger=zeros([1 p]);
```

```
W_bus=zeros([p 1]);
Z=zeros([p 1]);
power_loss=zeros([p 50]);
%shad_loss=zeros([1 50]);
sh_loss=zeros([1 50]);
FillFact=zeros([p 50]);
eff_real=zeros([p 50]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ploss_T=zeros([p 50]);
P_rf=zeros([p 50]);
P_rb=zeros([p 50]);
P_sf=zeros([p 50]);
P_sb=zeros([p 50]);
P_cf=zeros([p 50]);
P_te=zeros([p 50]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Area=1;
flux_initial=zeros([92 1]);
J_scP=zeros([92 1]);
J_scP_1=zeros([92 1]);
J_scP_2=zeros([92 1]);
J_scP_3=zeros([92 1]);
J_scP_4=zeros([92 1]);
J_scN=zeros([92 1]);
J_scN_1=zeros([92 1]);
J_scN_2=zeros([92 1]);
J_scN_3=zeros([92 1]);
J_scN_4=zeros([92 1]);
J_dr=zeros([92 1]);
J_sc1=zeros([92 p]);
J_scfix_w1=zeros([92 1]);
Jdark_P1=zeros([92 1]);
Jdark_N1=zeros([92 1]);
Jdark_N_1=zeros([92 1]);
Jdark_N_2=zeros([92 1]);
Jdark1=zeros([92 p]);
%%%%%%%%%%%%%%%%%%%%%%
Io2=zeros([1,p]);
%%%%%%%%%%%%%%%%%%%%%
%J1=zeros([1 p]);
Jdark=zeros([1 p]);
J3=zeros([1 p]);
I_series=zeros([1 p]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
absorption=zeros([300,1]);
%J_sc2=zeros([92 p]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
V_oc=zeros([1 p]);
QE_P=zeros([92 0]);
QE_N=zeros([92 0]);
QE1=zeros([92 p]);
QE=zeros([92 1]);
SR=zeros([92 1]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
I=zeros([1 p]);
Idark=zeros([1 p]);
 V_m=zeros([1 p]);
 I_m=zeros([1 p]);
 P=zeros([1200 1]);
 Pmax=zeros([1 p]);
 FF=zeros([1 p]);
```

```
 efficiency=zeros([1 p]);
 %%%%% G is irradiance in(W/m2)%%%%%%
 G=1000;
 q=1.6E-19;
 K=1.381E-23;
 T=300;
 V_t=K*T/q;

b=1;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Up=130+(370/(1+((Nd/8E17)^1.25)));
Tp=1/(((7.8E-13)*Nd)+((1.7E-31)*Nd*Nd));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Un=232+(1180/((1+(Na/8E16)^0.9)));
Tn=1/(((3.45E-12)*Na)+((0.95E-31)*Na*Na));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Un_plus=232+(1180/((1+(Na_plus/8E16)^0.9)));
Tn_plus=1/(((3.45E-12)*Na_plus)+((0.95E-31)*Na_plus*Na_plus));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%D_p=3.3898;        %load('diff_coeff_ptype.txt');
D_p=Up*(K*T/q);

%*************cm^2/sec*******************
%D_n=35.989;         %load('diff_coeff_ntype.txt');
D_n=Un*(K*T/q);

%%%%%%%%%%%%%%%%%%%%%%%%%%%
Dn_plus=Un_plus*(K*T/q);

%************cm****************
%L_p=4.366E-5;      %load('Diffusion_Length_hole.txt');
L_p=((Tp*D_p)^0.5);

%************cm****************
%L_n=10.2125E-02;   %load('Diffusion_Length_electron.txt');
L_n=((Tn*D_n)^0.5);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ln_plus=((Tn_plus*Dn_plus)^0.5);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
alpha=load('abs_coeff_92.txt');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ni=1E10;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%lm=load('wavelength_nm.txt');
%*******micron***********
lamda=lm*1E-3;

%**********watt/(m^2-um)*************************
spectral_irradiance=load('irradiance_wm2_nm_92.txt')*1000;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
spec_irrad=load('irrad_wm2_nm.txt');
wave_lent=load('wav_lent_nm.txt');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   textured surface modelling                                         %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
lamb_R=0.97;
face_theta=70.53/2;
frac=zeros([92 1]);
```

```
text_beta=zeros([92 1]);
alpha_eff=zeros([92 1]);
abs_length=zeros([92 1]);
mu=load('rif_indx_92.txt');
for tcc=1:1:92;
frac(tcc,1)=(1/(mu(tcc,1)*mu(tcc,1)));
text_beta(tcc,1)=acosd((cosd(face_theta)/mu(tcc,1)))-face_theta;
alpha_eff(tcc,1)=((alpha(tcc,1)/cosd(text_beta(tcc,1)))+((1/t)*log((1-
(lamb_R*(1-frac(tcc,1))*exp(-4*alpha(tcc,1)*t)))/(1-(lamb_R*(1-
(frac(tcc,1)*exp(-2*alpha(tcc,1)*t))))))));
abs_length(tcc,1)=(1/alpha_eff(tcc,1));
end
x=load('thk_400_1.txt');
thk=x*1E2;
%********Vo built in voltage*********
Vo=V_t*log(Na*Nd/(Ni*Ni));
R=zeros([92 1]);
%********W junction width in cm*************
W=sqrt(((2*11.7*8.8542E-12*Vo)/q)*((Na+Nd)/(Na*Nd)));
Xp=W*(Nd/(Na+Nd));
Xn=W*(Na/(Na+Nd));

%********W_n thickness of N region in cm*************
W_n=x*1E2;

%**********cm/sec************
%S_n=100;
S_n=(((Na*Dn_plus)/(Na_plus*Ln_plus))*coth(Wp_plus/Ln_plus));
%**********cm/sec************
S_p=(1E-16)*Nd;%3E4;
S_n_back=2E5;
%**********cm^2/sec************
%********cm*************
widt_emit=zeros([p 1]);
for y=1:1:p;
    widt_emit(y,1)=W_n(y,1);
end
W_p=(ones([p 1])*t)-(widt_emit+(ones([p 1])*W)+(ones([p 1])*Wp_plus));

   for j=1:1:p;


             for a=1:1:92;


%%%%%%%%%%%%%%%%%%%photon flux at the surface(photons/(cm2-
um))%%%%%%%%%%%%%%%%%%%%
flux_initial(a,1)=spectral_irradiance(a,1)*lamda(a,1)*(1E16/19.8);
%%%%%%%%%%%%EMITTER SHORT CIRCUIT SPECTRAL CURRENT
DENSITY%%%%%%%%%%%%%%%%%%%
%*******************(Amp/cm^2um)**************************************
%J_scE(a,1)={{(q*alpha_eff(a,1)*flux_initial(a,1)*(1-
R(a,1))*L_p(b,1))/((alpha_eff(a,1)*L_p(b,1))+1)}*{1/((alpha_eff(a,1)*L_p(b,
1))-1)}}*{{-alpha_eff(a,1)*L_p(b,1)*exp(-
alpha_eff(a,1)*W_n(j,1))}+({S_n*L_p(b,1)/D_p(b,1)}+{alpha_eff(a,1)*L_p(b,1)
}-{exp(-
alpha_eff(a,1)*W_n(j,1))*(({S_n*L_p(b,1)/D_p(b,1)}*cosh(W_n(j,1)/L_p(b,1)))
+sinh(W_n(j,1)/L_p(b,1)))})/(cosh(W_n(j,1)/L_p(b,1))+({S_n*L_p(b,1)/D_p(b,1
)}*sinh(W_n(j,1)/L_p(b,1))))};
```

```
J_scP(a,1)=(((q*alpha_eff(a,1)*flux_initial(a,1)*(1-
R(a,1))*L_p(b,1))/((alpha_eff(a,1)*L_p(b,1))+1))*(1/((alpha_eff(a,1)*L_p(b,
1))-1)))*((-alpha_eff(a,1)*L_p(b,1)*exp(-
alpha_eff(a,1)*W_n(j,1)))+((S_p*L_p(b,1)/D_p(b,1))+(alpha_eff(a,1)*L_p(b,1)
)-(exp(-
alpha_eff(a,1)*W_n(j,1))*(((S_p*L_p(b,1)/D_p(b,1))*cosh(W_n(j,1)/L_p(b,1)))
+sinh(W_n(j,1)/L_p(b,1)))))/(cosh(W_n(j,1)/L_p(b,1))+((S_p*L_p(b,1)/D_p(b,1
))*sinh(W_n(j,1)/L_p(b,1)))));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%
Jdark_P1(a,1)=(q*Ni*Ni*D_p(b,1)/(Nd*L_p(b,1)))*((S_p*(L_p(b,1)/D_p(b,1))*co
sh(W_n(j,1)/L_p(b,1))+sinh(W_n(j,1)/L_p(b,1)))/(S_p*(L_p(b,1)/D_p(b,1))*sin
h(W_n(j,1)/L_p(b,1))+cosh(W_n(j,1)/L_p(b,1))));
% %%%%%%%%%%%%BASE SHORT CIRCUIT SPECTRAL CURRENT
DENSITY%%%%%%%%%%%%%%%%%%%
% %*******************(Amp/cm^2um)************************************
% %J_scB(a,1)={{(q*alpha_eff(a,1)*{flux_initial(a,1)*exp(-
alpha_eff(a,1)*W_n(j,1))}*(1-
R(a,1))*L_n(b,1))/((alpha_eff(a,1)*L_n(b,1))+1)}*{1/((alpha_eff(a,1)*L_n(b,
1))-1)}}*{{-alpha_eff(a,1)*L_n(b,1)}-
({S_p*L_n(b,1)/D_n(b,1)}*{cosh(W_p(j,1)/L_n(b,1))-exp(-
alpha_eff(a,1)*W_p(j,1))}+sinh(W_p(j,1)/L_n(b,1))+{alpha_eff(a,1)*L_n(b,1)*
exp(-
alpha_eff(a,1)*W_p(j,1))})/(cosh(W_p(j,1)/L_n(b,1))+({S_p*L_n(b,1)/D_n(b,1)
}*sinh(W_p(j,1)/L_n(b,1))))};
%J_scN(a,1)=(((1.6E-19*alpha_eff(a,1)*(flux_initial(a,1)*exp(-
alpha_eff(a,1)*(W_n(j,1)+W)))*(1-
R(a,1))*L_n(b,1))/((alpha_eff(a,1)*L_n(b,1))+1))*(1/((alpha_eff(a,1)*L_n(b,
1))-1)))*((alpha_eff(a,1)*L_n(b,1))-
((S_n*L_n(b,1)/D_n(b,1))*(cosh(W_p(j,1)/L_n(b,1))-exp(-
alpha_eff(a,1)*W_p(j,1)))+sinh(W_p(j,1)/L_n(b,1))+(alpha_eff(a,1)*L_n(b,1)*
exp(-
alpha_eff(a,1)*W_p(j,1))))/(cosh(W_p(j,1)/L_n(b,1))+((S_n*L_n(b,1)/D_n(b,1)
)*sinh(W_p(j,1)/L_n(b,1)))));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
J_scN_1(a,1)=(((1.6E-19*alpha_eff(a,1)*(flux_initial(a,1)*exp(-
alpha_eff(a,1)*(W_n(j,1)+W)))*(1-
R(a,1))*L_n(b,1))/((alpha_eff(a,1)*L_n(b,1))+1))*(1/((alpha_eff(a,1)*L_n(b,
1))-1)))*((alpha_eff(a,1)*L_n(b,1))-
((S_n*L_n(b,1)/D_n(b,1))*(cosh(W_p(j,1)/L_n(b,1))-exp(-
alpha_eff(a,1)*W_p(j,1)))+sinh(W_p(j,1)/L_n(b,1))+(alpha_eff(a,1)*L_n(b,1)*
exp(-
alpha_eff(a,1)*W_p(j,1))))/(cosh(W_p(j,1)/L_n(b,1))+((S_n*L_n(b,1)/D_n(b,1)
)*sinh(W_p(j,1)/L_n(b,1)))));
J_scN_2(a,1)=(((1.6E-19*alpha_eff(a,1)*(flux_initial(a,1)*exp(-
alpha_eff(a,1)*(W_n(j,1)+W+W_p(j,1))))*(1-
R(a,1))*Ln_plus(b,1))/((alpha_eff(a,1)*Ln_plus(b,1))+1))*(1/((alpha_eff(a,1
)*Ln_plus(b,1))-1)))*((alpha_eff(a,1)*Ln_plus(b,1))-
((S_n_back*Ln_plus(b,1)/Dn_plus(b,1))*(cosh(Wp_plus/Ln_plus(b,1))-exp(-
alpha_eff(a,1)*Wp_plus))+sinh(Wp_plus/Ln_plus(b,1))+(alpha_eff(a,1)*Ln_plus
(b,1)*exp(-
alpha_eff(a,1)*Wp_plus)))/(cosh(Wp_plus/Ln_plus(b,1))+((S_n_back*Ln_plus(b,
1)/Dn_plus(b,1))*sinh(Wp_plus/Ln_plus(b,1)))));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
J_scN(a,1)=(J_scN_1(a,1)+J_scN_2(a,1));
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%
%Jdark_N1(a,1)=(q*Ni*Ni*D_n(b,1)/(Na*L_n(b,1)))*((S_n*(L_n(b,1)/D_n(b,1))*c
osh(W_p(j,1)/L_n(b,1))+sinh(W_p(j,1)/L_n(b,1)))/(S_n*(L_n(b,1)/D_n(b,1))*si
nh(W_p(j,1)/L_n(b,1))+cosh(W_p(j,1)/L_n(b,1))));
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Jdark_N_1(a,1)=(q*Ni*Ni*D_n(b,1)/(Na*L_n(b,1)))*((S_n*(L_n(b,1)/D_n(b,1))*c
osh(W_p(j,1)/L_n(b,1))+sinh(W_p(j,1)/L_n(b,1)))/(S_n*(L_n(b,1)/D_n(b,1))*si
nh(W_p(j,1)/L_n(b,1))+cosh(W_p(j,1)/L_n(b,1))));
Jdark_N_2(a,1)=(q*Ni*Ni*Dn_plus(b,1)/(Na_plus*Ln_plus(b,1)))*((S_n_back*(Ln
_plus(b,1)/Dn_plus(b,1))*cosh(Wp_plus/Ln_plus(b,1))+sinh(Wp_plus/Ln_plus(b,
1)))/(S_n_back*(Ln_plus(b,1)/Dn_plus(b,1))*sinh(Wp_plus/Ln_plus(b,1))+cosh(
Wp_plus/Ln_plus(b,1))));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Jdark_N1(a,1)=Jdark_N_1(a,1)+Jdark_N_2(a,1);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%quantum efficiency of base%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
J_dr(a,1)=(q*flux_initial(a,1)*(1-R(a,1))*exp(-alpha_eff(a,1)*W_n(j,1))*(1-
exp(-alpha_eff(a,1)*W)));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
J_sc1(a,j)=J_scP(a,1)+J_scN(a,1)+J_dr(a,1);

 %%%%%%%%%%%%%dark current%%%%%%%%%%%%%%%%
 Jdark1(a,j)=(Jdark_P1(a,1)+Jdark_N1(a,1));
  %%%%%%%%%%%%total quantum effciency in percentage%%%%%%%%%%%%%%
  QE1(a,j)=J_sc1(a,j)/(q*flux_initial(a,1)*(1-R(a,1)));
 J_scfix_w1(a,1)=(J_sc1(a,j));
 QE(a,1)=QE1(a,j);
 SR(a,1)=QE1(a,j)*lamda(a,1)*0.808;

             end

   end
     J_sc=sum(J_sc1);
     J_1=(J_sc1');
     J_2=sum(J_1);
     J1=sum(Jdark1);

     J2=(exp(V/V_t)-1)*J1;
      I_l=Area*J_sc;
      I0=Area*J1;
      z=0;
       for k=1:1:p;
           n=0;

           V_oc(1,k)=V_t*log(1+(J_sc(1,k)/J1(1,k)));
            if
((k==1)||(k==2)||(k==3)||(k==4)||(k==5)||(k==6)||(k==7)||(k==8)||(k==9)||(k
==10)||(k==11)||(k==12)||(k==13)||(k==14)||(k==15))
            for volt=-0.5:0.001:V_oc(1,k);

         n=n+1;  %for knowing different jdark values for different voltages
      m(n,1)=volt;
%          if ((k==1)||(k==50))
      Jdark(1,k)=(exp(volt/V_t)-1)*J1(1,k);
      dummy(n,k)=Jdark(1,k);
      J3(1,k)=J_sc(1,k)-Jdark(1,k);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
      if(volt>=0)
   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
      P(n,1)=volt*abs(I(1,k));
       Pmax(1,k)=max(P);
```

```
      end

            end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%5
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%5
5
            n=0;
             for volt=-0.5:0.001:V_oc(1,k);
                n=n+1;
                Idark(1,k)=(exp(volt/V_t)-1)*I0(1,k);
                I(1,k)=I_l(1,k)-Idark(1,k);
                cond=Pmax(1,k)-(volt*I(1,k));
                if(cond==0)
                V_m(1,k)=volt;
                I_m(1,k)=I(1,k);
                FF(1,k)=((V_m(1,k)*I_m(1,k))/(V_oc(1,k)*I_l(1,k)));
                efficiency(1,k)=(FF(1,k)*V_oc(1,k)*J_sc(1,k)/(G/10000));
                ideal_eff=max(efficiency);
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
  tz=0;
          Ploss_e=zeros([1 500]);
          plos_fig1=zeros([1 500]);

          optm=20000*ones([1 500]);
          shading_loss=ones([1 50]);
          busbar_wid=zeros([1 10]);
          opt_spacing=zeros([10 p]);
          fing_width=zeros([10 p]);
          nut=0;

        finger_wid_spc=zeros([500 10]);
        spacing_bubr=zeros([10 500]);
        for h=1:1:500;
                    widt=1;
                    %asp_rat=10;
                    Ro_e(k,1)=(1/(q*Up*Nd*W_n(k,1)));

Plost_e(1,h)=((((I_m(1,k)/Area)^2)*widt*Ro_e(k,1)*(S(1,h)^3))/24);

Plost_e_tst(k,h)=((((I_m(1,k)/Area)^2)*widt*Ro_e(k,1)*(S(1,h)^3))/24);
                    pow_rec_tst(k,h)=Pmax(1,k)-Plost_e_tst(k,h);
                   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
                   perct=0.04*Pmax(1,k);
                    if(Plost_e(1,h)<0.04)
                         Ploss_e(1,h)=Plost_e(1,h);
                         %%%%%%%%%%%%%%%%%%%%%%%%%
                        spc(1,h)=S(1,h);
                        if(spc(1,h)~=0)
                            nut=nut+1;
                        end
                    end
        end
       fig_spac=zeros([1 nut]);
        nut1=0;
        for h=1:1:500;
            if (spc(1,h)~=0)
                nut1=nut1+1;
            fig_spac(1,nut1)=spc(1,h);
            end
        end
        Ro_base=(1/(q*Un*Na));
```

```
        Ro_base_plus=(1/(q*Un_plus*Na_plus));
        aspact_ratio=1/5;
        num_bond_pt=20;
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            volt_m=zeros([nut1 10]);
            current_m=zeros([nut1 10]);
            power_maxn=zeros([nut1 10]);
            poer_los=zeros([nut1 10]);
            slope=zeros([p 1]);
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%
        finger_wth1=zeros([1 nut1]);
        spac1=zeros([1 nut1]);
        H_fing=zeros([1 nut1]);
        R_fc=zeros([1 nut1]);
        R_se=zeros([10 nut1]);
        Resis_sers=100*ones([10 nut1]);
        R_finger=zeros([10 nut1]);
         resist=10*ones([10 nut1]);
         fing_wid=zeros([1 nut1]);
          busb_wid=zeros([1 10]);
          shd_los=10*ones([10 nut1]);
          %power_maxm=zeros([nut1 1]);
         nuber1=0;
        if(nut1~=0)
            for lt=1:1:nut1;

        finger_wth1(1,lt)=(1-((num_bond_pt-1)*fig_spac(1,lt)))/num_bond_pt;
        %%%%%%%%%%%%%%%%%%%%
        H_busbar=zeros([1 10]);
        %R_emitter=zeros([115 10]);
        R_bus=zeros([1 10]);
        %%%%%%%%%%%%%%%%%%%%%

         if(finger_wth1(1,lt)>0)
        for kt=1:1:10;

             H_fing(1,lt)=W_fing(1,lt)*aspact_ratio;
             H_busbar(1,kt)=width_busbar(1,kt)*aspact_ratio;

R_emitter(lt,kt)=((num_bond_pt*(fig_spac(1,lt)^2))/(3*length))*(Ro_e(k,1)/(
(0.5*length)-width_busbar(1,kt)));
             Rrmmt(lt,kt)=R_emitter(lt,kt);

R_base(1,k)=(Ro_base*(8*num_bond_pt*W_p(k,1))/(length^2))+(Ro_base_plus*(Wp
_plus)/(length^2));

R_finger(kt,lt)=((num_bond_pt*fig_spac(1,lt))/(3*length))*(Ro_smf/(W_fing(1
,lt)*H_fing(1,lt)))*((0.5*length)-width_busbar(1,kt));

R_bus(1,kt)=(Ro_smb/(3*num_bond_pt))*(length/(width_busbar(1,kt)*H_busbar(1
,kt)));

R_fc(1,lt)=(8*num_bond_pt*fig_spac(1,lt)*Ro_c)/(length*((W_fing(1,lt)*lengt
h)+(2*width_busbar(1,kt)*(fig_spac(1,lt)-W_fing(1,lt)))));
             R_bc=(8*num_bond_pt*Ro_c)/(length^2);

R_se(kt,lt)=(R_emitter(lt,kt)+R_base(1,k)+R_finger(1,lt)+R_bus(1,kt)+R_fc(1
,lt)+R_bc)/(8*num_bond_pt);
             if(R_se(kt,lt)~=0)
                 Resis_sers(kt,lt)=R_se(kt,lt);
             end
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            slope(k,1)=I_l(1,k)/V_oc(1,k);
            volt_m(lt,kt)=V_oc(1,k)-(R_se(kt,lt)*(cos(atan(slope(k,1)))));
            current_m(lt,kt)=I_l(1,k)-
(R_se(kt,lt)*(sin(atan(slope(k,1)))));
            power_maxn(lt,kt)=volt_m(lt,kt)*current_m(lt,kt);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
             if((R_se(kt,lt)~=0)&&(R_se(kt,lt)<=0.02))
                 resist(kt,lt)=R_se(kt,lt);
                 fing_wid(1,lt)=finger_wth1(1,lt);
                 spac1(1,lt)=fig_spac(1,lt);
                 busb_wid(1,kt)=width_busbar(1,kt);
                 nuber1=nuber1+1;

if((resist(kt,lt)~=10)&&(fing_wid(1,lt)~=0)&&(spac1(1,lt)~=0))

shd_los(kt,lt)=(fing_wid(1,lt)/spac1(1,lt))+(width_busbar(1,kt)/B);
                 end
             end

        end
        power_maxm=max(power_maxn);
          end

            end
        end
  if (nuber1~=0)
        por_maxm(k,1)=max(power_maxm);
        tt1=nuber1/10;
        resis_min_bbwid=min(resist);
        series_resistance1=min(resis_min_bbwid);
        shad_loss1=min(shd_los);
        min_shad_loss=min(shad_loss1);
            for lt=1:1:nut1;
                for kt=1:1:10;
                       if (shd_los(kt,lt)~=10)
                        intm11=min_shad_loss-shd_los(kt,lt);
                       if(intm11==0)
                            series_resistance2(1,k)=resist(kt,lt);
                            busbar_width(1,k)=width_busbar(1,kt);
                            finger_width(1,k)=fing_wid(1,lt);
                            spacing_finger(1,k)=(1-
(finger_width(1,k)*num_bond_pt))/(num_bond_pt-1);

power_los1(1,k)=((((I_m(1,k)/Area)^2)*widt*Ro_e(k,1)*((spacing_finger(1,k))
^3))/24);

power_los3(1,k)=(2*B*sqrt(((Ro_smf+(Ro_c*M/(B*B)))*I_m(1,k))/(M*V_m(1,k)*Ar
ea)));

Prf(1,k)=((B^2)*Ro_smf*I_m(1,k)*spacing_finger(1,k))/(M*V_m(1,k)*Area*finge
r_width(1,k));
                            Psf(1,k)=finger_width(1,k)/spacing_finger(1,k);

Pcf(1,k)=(Ro_c*I_m(1,k)*spacing_finger(1,k))/(V_m(1,k)*Area*finger_width(1,
k));

Ptl(1,k)=(Ro_e(k,1)*I_m(1,k)*(spacing_finger(1,k)^2))/(12*V_m(1,k)*Area);

Prb(1,k)=((length^2)*B*Ro_smb*I_m(1,k))/(M*V_m(1,k)*Area*busbar_width(1,k))
;
```

```
                            Psb(1,k)=busbar_width(1,k)/B;

power_los2(1,k)=Prf(1,k)+Psf(1,k)+Pcf(1,k)+Ptl(1,k)+Prb(1,k)+Psb(1,k);
                            power_los4(1,k)=Pmax(1,k)-
(Pmax(1,k)*power_los2(1,k));

power_los5(1,k)=(Ro_smb*spacing_finger(1,k)*spacing_finger(1,k)*I_m(1,k))/(
12*Area*V_m(1,k));
                            pow_max=max(power_los4);
                        end
                      end
                end
            end
  else
       pow_max=0;
       jum=1;

  end
                end





             end
            end
       end
       if(jum==0)
        for k=1:1:p;
            to=pow_max-power_los4(1,k);
            if(to==0)
                indx=k;
            end
        end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%***********************************
       I_final=zeros([1 p]);
       I_fin=zeros([1 p]);
       I_idl=zeros([1 p]);
       I_1=zeros([1 p]);
       I_2=zeros([1 p]);
       I_3=zeros([1 p]);
       pt=zeros([1 1500]);
       pt_1=zeros([1 1500]);
       pt_2=zeros([1 1500]);
       V_max=zeros([1 p]);
       Pmax_final=zeros([1 p]);
       I_max=zeros([1 p]);
       FF_final1=zeros([1 p]);
       FF_final=zeros([1 p]);
       efficiency_final1=zeros([1 p]);
       efficiency_final=zeros([1 p]);
       intr=zeros([1 1200]);


       for k=1:1:p;
           txn=0;
        pow_fin=zeros([1 1200]);
```

```
           if
((k==1)||(k==2)||(k==3)||(k==4)||(k==5)||(k==6)||(k==7)||(k==8)||(k==9)||(k
==10)||(k==11)||(k==12)||(k==13)||(k==14)||(k==15))
           ntp=0;
           ctn=0;
           tst1=0;
           for volt=0:0.001:V_oc(1,k);
            ctn=ctn+1;
           I_1(1,k)=(exp(volt/V_t)-1)*I0(1,k);
           I_idl(1,k)=(I_l(1,k))-I_1(1,k);
           tst2=((I0(1,k)*(exp((volt+(tst1*series_resistance2(1,k)))/V_t)-
1))+(Io2(1,k)*(exp((volt+(tst1*series_resistance2(1,k)))/(2*V_t))-1)));
           tst1=(I_l(1,k))-tst2;
           I_final(1,k)=tst1;
           pt(1,ctn)=I_final(1,k);
           pt_1(1,ctn)=I_idl(1,k);
           pt_2(1,ctn)=I_2(1,k);
           txn=(volt*tst1)-(volt*I_idl);
       if((tst1>=0))
       pow_fin(1,ctn)=volt*tst1;




       end

           end
           Pmax_final(1,k)=max(pow_fin);

           crtn=0;
           Iint1=0;

           for volt=0:(0.001):V_oc(1,k);
               crtn=crtn+1;
             I_1(1,k)=(exp(volt/V_t)-1)*I0(1,k);
             I_idl(1,k)=(I_l(1,k))-I_1(1,k);
           %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Iint2=((I0(1,k)*(exp((volt+(Iint1*series_resistance2(1,k)))/V_t)-
1))+(Io2(1,k)*(exp((volt+(Iint1*series_resistance2(1,k)))/(2*V_t))-1)));
           Iint1=(I_l(1,k))-Iint2;

           con=Pmax_final(1,k)-(volt*Iint1);
                 if(con==0)
                 V_max(1,k)=volt;
                 I_max(1,k)=Iint1;

FF_final(1,k)=((V_max(1,k)*I_max(1,k))/(V_oc(1,k)*I_l(1,k)));

efficiency_final(1,k)=(FF_final(1,k)*V_oc(1,k)*J_sc(1,k)/(G/10000));
                 %******************************************
                 opt_efficiency=efficiency_final(1,indx);
                 %******************************************
                 end
           end
           end
       end
       tht=0;
       tvn=0;
       for a=1:1:p;
           txn1=0;
```

```
           tnt1=0;
           tnt_1=0;
           cnlt=0;
           if((efficiency_final(1,a)~=0))
               int_res=opt_efficiency-efficiency_final(1,a);
               if (int_res==0)
               tht=tht+1;
               scrip=a;
               gt=(scrip+1);
                  ty=efficiency_final(1,scrip)-efficiency(1,scrip);
                  if(ty>0)

                   for J=gt:1:p;
                       tvn=tvn+1;
                       ty2=efficiency_final(1,J)-efficiency(1,J);
                       if(ty2<=0)
                              thj1=1;
                              rsnt1=zeros([1200 1]);
                              rsnt11=zeros([1200 1]);
                              gj1=0;
                           for volt=0:(0.001):V_oc(1,J);
                                thj1=thj1+1;
                                I_11_1=(exp(volt/V_t)-1)*I0(1,J);
                                I_idl1_1=(I_l(1,J))-I_11_1;

tnt_11=(I0(1,J)*(exp((volt+(tnt_1*series_resistance2(1,J)))/V_t)-
1))+(Io2(1,J)*(exp((volt+(tnt_1*series_resistance2(1,J)))/(2*V_t))-1));
                                tnt_1=(I_l(1,J))-tnt_11;
                                rsnt1(thj1,1)=tnt_1;
                                 rsnt11((thj1-1),1)=rsnt1((thj1-1),1)-
rsnt1(thj1,1);
                                 if(rsnt11((thj1-1),1)<0)
                                     gj1=gj1+1;
                                 end
                           end
                            txn1=(Pmax_final(1,J))-(Pmax(1,J));
                            if((txn1<0)&&(gj1==1))
                            scrip=J;
                            cnlt=cnlt+1;
                            break;
                            end
                       end
                   end
                 else
                   txn2=(Pmax_final(1,scrip)-(Pmax(1,scrip)));
                   if (txn2>0)

                       for J=gt:1:p;
                           ty3=Pmax_final(1,J)-Pmax(1,J);
                          if(ty3<0)
                              thj=1;
                              rsnt=zeros([1200 1]);
                              rsnt1=zeros([1200 1]);
                              gj=0;
                              for volt=0:(0.001):V_oc(1,J);
                                  thj=thj+1;
                                 I_11_1=(exp(volt/V_t)-1)*I0(1,J);
                                 I_idl1_1=(I_l(1,J))-I_11_1;

tnt_11=(I0(1,J)*(exp((volt+(tnt_1*series_resistance2(1,J)))/V_t)-
1))+(Io2(1,J)*(exp((volt+(tnt_1*series_resistance2(1,J)))/(2*V_t))-1));
```

```
                                 tnt_1=(I_l(1,J))-tnt_11;
                                 rsnt(thj,1)=tnt_1;
                                 rsnt1((thj-1),1)=rsnt((thj-1),1)-
rsnt(thj,1);
                                 if(rsnt1((thj-1),1)<0)
                                     gj=gj+1;
                                 end
                               end

%
                              if((gj==1)||(gj==0))
                             scrip=J;

                             break;
                              end
                           end
                        end
                   else
                      gt12=a;
                      %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
                      for J=gt12:1:p;
                           ty312=Pmax_final(1,J)-Pmax(1,J);
                          if(ty312<0)
                              thj12=1;
                              rsnt=zeros([1200 1]);
                              rsnt1=zeros([1200 1]);
                              gj12=0;
                              for volt=0:(0.001):V_oc(1,J);
                                  thj12=thj12+1;
                                 I_11_1=(exp(volt/V_t)-1)*I0(1,J);
                                 I_idl1_1=(I_l(1,J))-I_11_1;

tnt_11=(I0(1,J)*(exp((volt+(tnt_1*series_resistance2(1,J)))/V_t)-
1))+(Io2(1,J)*(exp((volt+(tnt_1*series_resistance2(1,J)))/(2*V_t))-1));
                                 tnt_1=(I_l(1,J))-tnt_11;
                                 rsnt(thj12,1)=tnt_1;
                                 rsnt1((thj12-1),1)=rsnt((thj12-1),1)-
rsnt(thj12,1);
                                 if(rsnt1((thj12-1),1)<0)
                                     gj12=gj12+1;
                                 end
                               end
                              if((gj12==1)||(gj12==0))
                             scrip=J;
                             %cnlt=cnlt+1;
                             break;
                              end
                           end
                      end
                   end
                      %%%%%%%%%%%%%%%%%%%%%%%
                 end
             %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
               effic=efficiency_final(1,scrip);
               fill_factor=FF_final(1,scrip);
               Rseries=series_resistance2(1,scrip);
               width_of_busbar=busbar_width(1,scrip);
               height_busbar=width_of_busbar*aspact_ratio;
               width_of_fingers=finger_width(1,scrip);
               height_fingers=width_of_fingers*aspact_ratio;
               spacing_btw_fingers=spacing_finger(1,scrip);
```

```
                thickness_emitter=W_n(scrip,1);
                thickness_P_layer=W_p(scrip,1);

                for volt=0:(0.001):V_oc(1,scrip);
                I_11=(exp(volt/V_t)-1)*I0(1,scrip);
                I_idl1=(I_l(1,scrip))-I_11;
                tnt=(I0(1,scrip)*(exp((volt+(tnt1*Rseries))/V_t)-
1))+(Io2(1,scrip)*(exp((volt+(tnt1*Rseries))/(2*V_t))-1));
                tnt1=(I_l(1,scrip))-tnt;
                end
                end
            end
       end
            effic_sl(ed,1)=effic;
            ideal_effic_sl(ed,1)=ideal_eff;
            N_tkh(ed,1)=thickness_emitter;
            P_plus_tkh(ed,1)=Wp_plus;
            ser_res(ed,1)=Rseries;
       else

            res1=min(Resis_sers);
            res2=min(res1);
            disp(['series resistance of the cell=',num2str(res2)]);

       end
 end

effi_max=max(effic_sl);
   for ed=1:1:uy1;
       cnq=effi_max-effic_sl(ed,1);
       if(cnq==0)
        disp(['efficiency of solar cell(with series resistance)
=',num2str(effic_sl(ed,1))]);
        disp(['ideal efficiency of solar cell
=',num2str(ideal_effic_sl(ed,1))]);
        disp(['series resistance =',num2str(ser_res(ed,1))]);
        disp(['thickness of N region =',num2str(N_tkh(ed,1))]);
        disp(['thickness of P+ region =',num2str(P_plus_tkh(ed,1))]);
       end
   end
```