Mathematical Formulation and Comparative Analysis of Losses in Solar Cells

Sharad Kr. Gupta
Asst. Prof.
Ph: +91- 9839164608
sharad_mpec@indiatimes.com

Mohit Kr. Srivastava
Asst. Prof.
Ph: +91-9935428632
mohit1003@yahoo.co.in

Ashish Gupta
Asst. Prof.
Ph: +91-9838630806
ashish3179@rediffmail.com

Department of Electronics Engineering, MPEC, Kothi Mandhana, Kanpur

Abstract

In this paper authors have focused over the mathematical formulation of different losses occurring in solar cells. The major losses which are highlighted in this paper are reflection loss, resistive loss, recombination loss and thermal loss which affect the efficiency of solar cell adversely. The present efficiency of solar cell is about 23.89% in laboratory and 13.76% commercially. This efficiency limit does not justify the cost of solar cells in comparison of other conventional energy sources. The authors explain the different analysis of losses occurring in solar cells and also remedies which are incorporated in order to reduce losses.

Keywords

Bulk recombination, Metal fingers and Bus bars, passivation, Schotty contacts, Reflection Losses

1 Introduction

The demand of energy is increasing day by day due to heavy industrialization all around the world but conventional energy sources are failed to meet with this heavy requirement in the power sector so the focus is to find out the alternative energy sources in this consequences renewable energy sources are gaining importance to meet this energy requirement

These non conventional energy resources are solar, wind, bio-energy, tidal energy, fuel cell etc. Among all these nonconventional energy resources solar cells are considered to the most important and sustainable engrgy source due to the availability of heavy solar energy. Direct electricity generation from sunlight is possible with the help of Solar Cells(cells). Advantage of solar cells is, they do not have any mechanical parts which makes them easy to use, maintenance free and leading to longer life. Silicon (Si) is widely used semiconductor material for solar cells. Advantage of Si over other semiconductor devices is due to well developed microelectronics industry which has considerable knowledge of working with Si. This makes Si a better candidate for solar cells as compared To other semiconductor material such as gallium arsenide (GaAs) or germanium (Ge). Fig.1 shows the maximum theoretical efficiency vs band-gap at air mass (1.5) of various semiconductor materials. Si which has band gap of 1.1ev has efficiency in the range of 26% as compared to the GaAs which has 30% efficiency, but due to good knowledge of processing and lower cost, Si is a better choice.

Solar cells reaching efficiency of 25% have been fabricated at UNSW Australia. Research is continuing to improve the efficiency up to its theoretical limit Which could be achieved by reducing the losses in the solar cells which are quite high as compared to conventional power sources .Solar cells manufactured through industrial process have efficiencies of the order 12 -15% this shows about 88 - 85% losses occur in solar cells. If these losses are overcome, efficiency improvement could be obtained. It becomes necessary to study different losses that occur in the solar cells and the methods which can be implemented to reduced them. Some practices which are followed to reduce the losses are, better material selection, proper manufacturing techniques or changing design procedure of the cell.

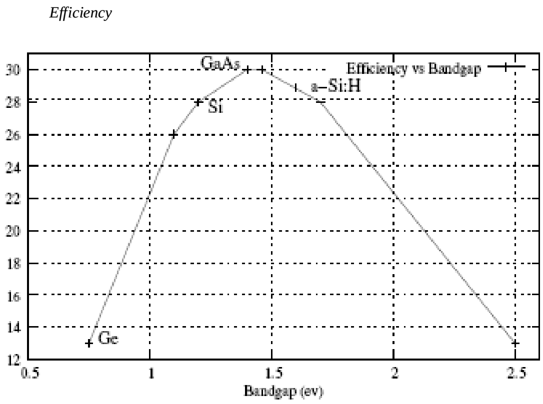


Figure 1: Efficiency vs Band-gap energy

2 Reflection Losses

The reflection loss occurs from top surface of the solar cells which receives the light. Reflection losses affect the I_{SC} short circuit current of the solar cell. Reflection reduces the absorbed carriers and hence the I_{SC}. It becomes necessary to improve the absorption and reduce reflection to improve short circuit current. For a bare Si these losses account for more than 30%. Photons striking the top surface are reflected due to high reflectivity of Si(0:3) in the UV and visible region, resulting in absorption of a very small portion of the incident light leading to poor efficiency. The reflectivity of Si is given as

$$R(\lambda)S_i = \frac{(n_{Si}(\lambda)-1)^2 + k(\lambda)^2}{(n_{Si}(\lambda)+1)^2 + k(\lambda)^2} \qquad (1)$$

As seen in Eq.1 the reactive losses depends on the refractive index (ηSi(λ)) of the Si and on the extinction coefficient (k(λ)), which are function of wavelength (λ) of the light incident on surface. Typical value for refractive index of Si is (ηSi = 3:9) and extinction coefficient (k = 0:05) these values are in visible region of the solar spectrum. Depending on these parameters, photon flux (Φ(x, λ) absorbed by the Si is given as

$$\phi(\chi,\lambda) = [1 - R(\lambda)_{Si}]\phi_0(\lambda)\exp^{-\alpha(\lambda)\chi} \qquad (2)$$

Where R (ג) Si is the loss due to refection.

Φ0 is the number of photons incident on the surface of Si. α(λ) is the absorption coefficient of Si and is defined as the number of photon absorbed by Si for a particular wavelength (λ). Absorption coefficient is a property of material and cannot be modified. α(λ) in visible spectrum is about 6 x 10^3/cm. The number of carriers that are absorbed by the solar cells is given by the quantum efficiency defined as Internal Quantum Efficiency (IQE) and External Quantum Efficiency (EQE), they indicate the amount of the carriers generated due to the photon absorption. External quantum efficiency is the current generated due to the photon absorption at the surface and is given as

$$EQE = \frac{\Delta J}{q\Delta\phi(\lambda)} \qquad (3)$$

where
ΔJ is the current density generated in the cell,
ΔΦ(λ) the photons absorbed ,
q the charge of the electron.

Internal quantum efficiency is due to the photons incident on the surface and is given as

$$IQE = \frac{EQE}{1 - R(\lambda) - T(\lambda)} \qquad (4)$$

where,
R(λ) is the reflectivity of the Si, T(λ) is the transitivity of the Si.
Carrier generation rate G(x; λ) depends on the IQE, absorptions coefficient (α(λ)) and the incident flux (Φ) and is given accordingly

$$G(\chi,\lambda) = (IQE)\alpha(\lambda)\phi(\lambda)[1 - R(\lambda)]\exp^{-\alpha(\lambda)z} \qquad (5)$$

The losses due to reflection in a bare Si are about 30% as discuss earlier. To reduce the reflectivity in solar cells a common approach is, use of an **antireflective coating** (ARC ≤ 60nm) deposited using CVD (chemical vapor deposition) and exturing (which is in the form of pyramids usually formed by etching the surface with the acid (H_2SO_4 or HNO_3 in H2O2) on top surface of the solar cells. The reflective losses occurring in the solar cells account to about 15% for properly textured solar cells a reduction in the reflective losses from 30%to15%. Materials used for ARC are SiO2 or Si3N4 earlier MgF2(η = 1:38) or ZnS (η = 2:25) were used. A better surface passivation is obtained by using Si_3N_4 as compared to SiO_2 as it gives the better adhesion property with the N type Si material. Refection of photons also occurs from the back surface of the solar cell i.e when the photon strikes the cells back surface it gets reflected from the back surface and in some cases may also go out of the cell. Such type of reflection loss is negligible in crystalline Si cells due to larger thickness of the base material. Proper thickness and refractive index are important physical parameters required for good ARC. Si3Ni4 has refractive index ($\eta_{Si3Ni4} = 2$) and SiO2 ($\eta_{SiO2} = 1.4$) in the visible region. Total internal reflection is desired when the photons strikes the surface of cell (interface between the Si and the ARC) The refractive index and thickness of the ARC material has to be adjusted to achieve internal reflection. The idea is to obtain the thickness t of ARC layer in such a manner that the light which is reflected from the surface of ARC and from the interface of ARC and Si is out of phase, resulting in destructive interference. So maximum possible light is absorbed by the Si. The total internal reflection is given as,

$$t = \frac{\lambda \times \cos\theta}{4 \times \eta_{ARC}} \qquad (6)$$

Use of ARC the reducing of reflectivity of Si is given in the Fig.3. Due to decrease in reectivity there is an increase in absorption of photons and more generation of carriers. The reectivity of a solar cell with ARC is about 13% or less as comapred to the more than 30% for bare Si. Fig.3 also shows the reectivity of Si under glass which lies between the bare Si and the Si using ARC of Si3N4 or SiO2. Also for internal reflection to occur the refractive index of the ARC has to be

$$\eta^2_{ARC} = \eta_{air}\,\eta_{Si} \qquad (7)$$

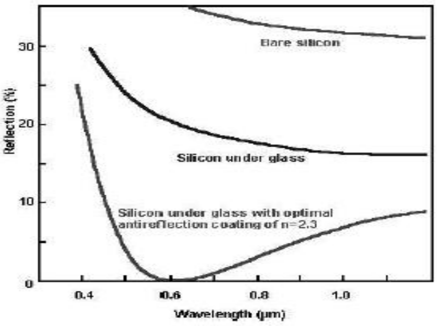


Figure 3: Effect of ARC

and the Reflection coefficient is given as

$$R_{\min} = \{\frac{\eta^2_{ARC} - \eta_{air}\eta_{Si}}{\eta^2_{ARC} + \eta_{air}\eta_{Si}}\}^2 \qquad (8)$$

rapid thermal oxidation (RTO) and Si3N4 systems . The RTO/Si3N4 system(consists of SiO2 and SiN) gives better front surface passivation and low optical reectivity (5.4%) Fig.4. A solar cell fabricated by this ARC/passivating layer gives an high Voc but lower Isc and F.F. SiO_2/SiN combine stack ARC is investigated for it passivating property. It is found that such stack layer gives low reactivity on textured surface as compared to other materials used for ARC.

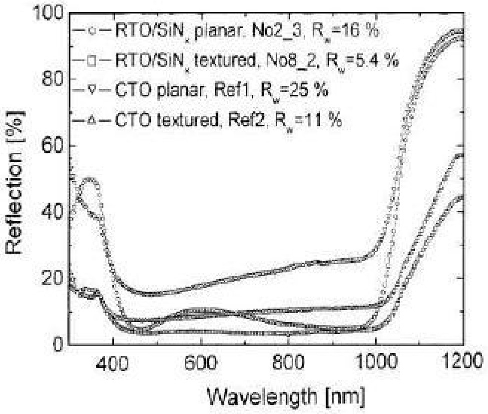


Figure 4: reflectivity of RTO SiN stack and other ARC

3 Recombination Losses

Photon incident on the solar cell generates electron hole pairs, these generated pairs are called as carriers. Generated carriers needs to be separated before they recombine, with emission of energy. Recombination causes loss of carrier and affects the performance of the cell. Open circuit voltage Voc of the cell is affected by recombination of carriers. As recombination increases the Voc reduces. Various techniques are used to reduce the recombination in the solar cells and improve Voc. Generation of carriers is in the entire volume of the solar cell material. The carriers generated near depletion region are separated out very quickly as they get swept away by the electric field present in the depletion region. Were as the carriers which are generated away from the depletion region that is in the bulk region, on the surface, or at the back surface have less probability of getting separated. These carriers will be lost and would not contribute to the current low if they recombine. Recombination of carriers generated in the Solar cells due to photo excitation is one of the most dominating loss occurring in the solar cell.

These losses account for major portion total input power. Different recombination losses that occur at different regions of the solar cells are

1. Surface recombination.
2. Bulk recombination.
3. Depletion region recombination.
4. Recombination at metal Semiconductor contact.

3.1 Surface recombination

Surface recombination is high in Si due to the presence of incomplete bonds also called as dangling bonds. These bonds appear due to sudden disruption of crystal structure. The incomplete bonds traps the generated carriers and get recombined. Another important factor that results in the surface recombination is surface recombination velocity S(SRV), it is a function of Nst surface trapping state

$$S_p = \sigma_p v_{th} N_{st} \tag{9}$$

Where

N_{st} is the number of surface trapping states

v_{th} is thermal velocity of carriers.

σ_p is capture cross-section for holes.

SRV is defined as the velocity with which the generated carriers recombine. As seen from the Eq.9 more are the number of Nst more is the SRV and more recombination. It is desired that the surface recombination velocity to be low. It depends on the material property and on the nature of surface as is clear from the Eq.9. Typical values of SRV for bare Si are in the range of (6x8x104cm=s) To reduce the effect of surface recombination and SRV, passivation is needed at the surface. This is accomplished by depositing a layer of Si3N4 or SiO2 at the top surface. These layers acts as ARC as well as passivating layers performing both the functions. Si_3N_4 has better passivating property than SiO_2 because when Si_3N_4 is deposited the hydrogen from the SiH_4 and from NH_3 precursor fills the dangling bonds and helps in passivating the surface of Si. It is also found that the temperature at which the passivating layer is deposited affects the SRV Higher temperature causes SRV to reduce, an SRV value of about 165cm/s at temperature is obtained by deposition of SiN at temperature of 4500C, The passivating layer is deposited by using chemical vapor deposition(CVD). The SRV value of 165cm/s obtained by using plasma enhanced chemical vapor deposition (PECVD). As explained in previously the rapid thermal oxidation with SiN deposition is one of the new techniques in reducing the SRV.

3.2 Depletion region recombination

Recombination occurring in the depletion region is less significant as compared to the surface recombination due to the presence of electric field. Charge carriers generated in depletion region are separated by electric field very quickly avoiding any chance of recombination. Any recombination occurring in the depletion region is mostly driven by the trap assisted recombination or band to band recombination.

3.3 Bulk recombination

Trap assisted recombination is dominating in the bulk region of the solar cell. As explained earlier the impurities if present in the semiconductor create a energy state which acts as the trap. A model given by Shockley and Reed hall is use to represent the trap assisted bulk recombination phenomenon.

$$U_{SHR} = \frac{pn - n_i^2}{\tau_{po}(n + n_1) + \tau_{no}(p + p_1)} \tag{10}$$

where U_{SHR} is Shockley Reed-hall recombination rate the זpo and ז no are the minority carrier lifetime in N and P region, p_1,n_1 are the equilibrium carrier concentration in P and N type semiconductor. p and n are the intrinsic carrier concentration at the equilibrium state. To reduce the trap assisted recombination a high purity semiconductor material is required. Wafer grown by utilizing Float zone (Fz) method have low impurity content than those from the czochkralski (Cz) grown ingots. Float zone (Fz) grown wafers have higher minority carrier lifetime _n and the diffusion constant D_n. These parameter determines the diffusion length L_n for the minority carrier(n are considered as minority carriers in the P type region).

$$L_n = \sqrt{\tau_n D_n} \tag{11}$$

It is desired that the minority carrier diffusion length should be as large as possible, it is define as the distance traveled by the minority carriers before they gets recombine. So higher L_n menace greater distance traveled by the carrier and more is the probability that the carriers are available for contributing to the current flow.

This requires larger minority carrier lifetime which indicates bulk material having low impurities and less crystal defects. losses can be reduced with the help of highly pure material as a substrate(base region).

3.4 Recombination at Metal Semiconductor contacts

Metal semiconductor contacts regions provide very large recombination sites. Semiconductor and metal contact junctions are formed at both front and back side of the solar cell. Back side contact contributes more to the recombination as it has more contact area with the semiconductor. Surface recombination velocity is also present at the rear contact and needs to be reduced. Rear surface passivation can reduce the SRV. Most of the high efficiency solar cells like PERL(passivated emitter rear locally diffused), PERT(passivated emitter rear totally diffused) have used rear passivation techniques utilizing a oxide layer between the metal and semiconductor layer. Carriers generated due to light and which are separated by the electric field are required to get collected by the metallic contact to provide power to the external load. If these carriers get recombine in the defects present at the metal semiconductor junction, there is reduction in ISC leading to power loss and reduced effciency. To reduce recombination in such areas a very strong electric field is created between metal semiconductor contacts. Electric field sweeps the carriers very fast with out allowing them to recombine. This enhances the collection probability for current in the solar cells. Electric field is created by heavily doping the semiconductor region which is in contact with the metal Fig.5. The heavily doped regions are called as the surface field and are present at both the ends front and back were the metal semiconductor meets. Another technique that is used to reduce the recombination is the use of passivating layer at the back side contact of the cell. Passivating layer used is an oxide preferably SiO2. The function of passivating layer is similar to that performed at the front side for reducing the SRV, which is high at the back side contact. Solar cells giving world record efficiency are manufactured using front and back passivating layers Fig.6

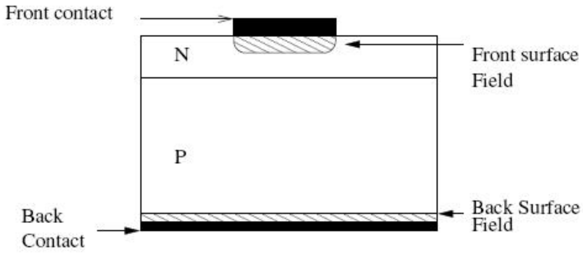


Figure 5: Surface Field

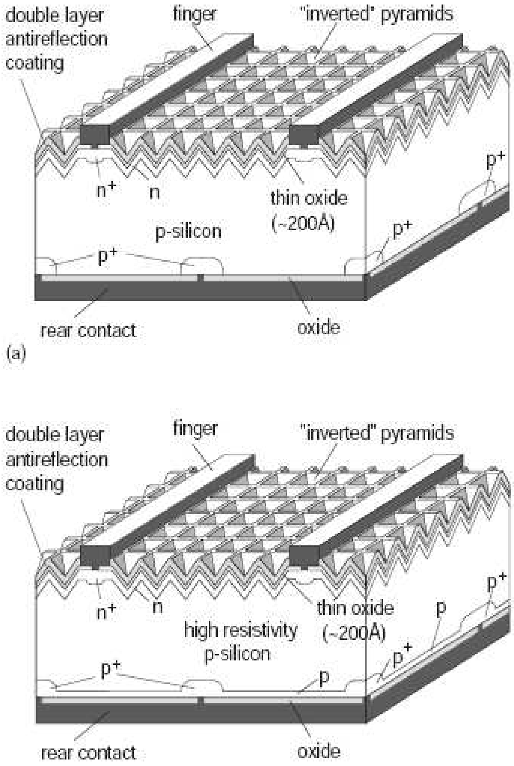


Figure 6: PERL and PERT solar cells

4 Series Resistance Losses

Series resistance losses contribute to around less than20% of the total input power. But these losses increases tremendously when solar cell is operated at high intensities. The high intensity is obtained when a sunlight is focoused on the solar cells with the help of lenses or mirrors. The intensity of the sunlight is measured in terms of geometrical concentration ratio (X). It is define as the ratio of aperture area to the receiver area,

$$X = \frac{A_c}{A_r} \tag{12}$$

where,

A_c is the aperture area of lenses or mirrors, A_r receiver area(solar cell area) I_{sc} is proportional to the intensity incident photons striking the solar cells, and hence on the concentration ratio (X),

$$I_{SC}(X) = XI_{SC}(1) \tag{13}$$

where

Isc(X) is short-circuit current at X concentrations and Isc(1) is short circuit current.

Power losses in the solar cell, due to series resistance is in direct proportion with the X^2. So higher X ratio increases power loss, reduces, fll factor and efficiency of the cells. Series resistance of the cell is combination of,

1. Emitter layer resistance
2. Metal-semiconductor contact (front and back)
3. Metal bus-bars and fingers
4. Bulk semiconductor resistance.

The metal bus-bars and fingers, emitter layer and metal-semiconductor contact resistance contribute in large magnitude to series resistance. Bulk resistance is low due to its high conductivity. A description of various resistances in semiconductor is shown in the Fig.7.

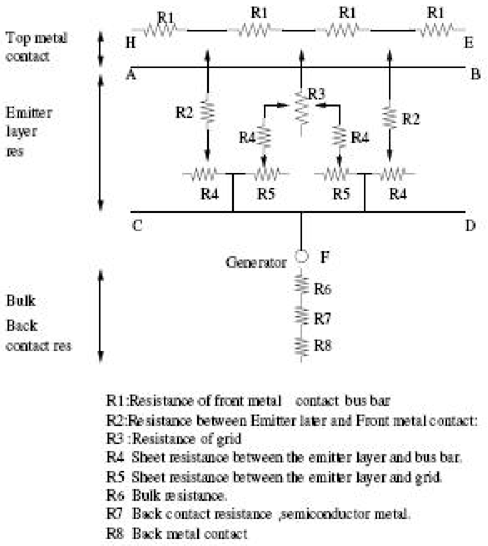


Figure 7: Resistance in solar Cell

4.1 Emitter resistance

Sheet resistance is the measure of resistance of thin films such as emitter layer which has thickness 1m and is given as ,

$$R = \rho \times \ell / A,$$

$$A = t \times \omega'$$

$$R = \rho \times \omega / (t \times l),$$

$$\Omega R_S = \rho / t,$$

and w/l is a unit less quantity which indicates number of squares ,l = nX w, n is the number of squares. This gives the sheet resistance of the emitter layer as Ω/square. Emitter resistance of solar cell is one of the most dominating component of series resistance of solar cell. Sheet resistance is measure of emitter resistance

and is measured experimentally using four point probe method and it is desired to have sheet resistance value in the range of 80 - 100 Ω /square. Factors affecting the emitter resistance are, thickness of the emitter layer, current direction in the emitter region, current collection by the metal fingers and busboys. Increase in emitter resistance is due to thin thickness of emitter layer which is around 1m as compared with the thickness of bulk region 280m. The direction of current flow in the emitter region is lateral as shown in the Fig.8 this increases path length of current due to lateral flow in emitter. Distributed nature of resistance due to variation of contact area of metal fingers and bus bar. Surface texturing has an effect on the emitter resistance. Resulting in increase of resistance due to increase in surface lateral area and exposure to (111) crystal planes. One approach for reducing the emitter resistance is through optimization of junction thickness. This could be achieved by suitable emitter doping concentration. Also the doping concentration and the junction depth needs to be optimize depending on which technology is used for front contact grid placement i.e. screen printing or the photolithography. it is seen that the junction depth and doping density does not reduce the efficiency in large magnitude Fig.9. This effect can be used to increase the junction depth and reduce the sheet resistance effect in series resistance of the solar cell.

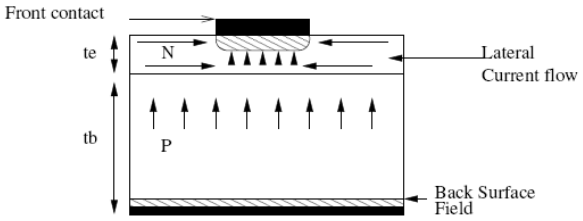


Figure 8: Current Flow emitter

4.2 Metal semiconductor contact

The other main component of the series resistance is the semiconductor to metal contact resistance. Metal contacts are required in the solar cells for collection of the carriers and transport them to the load to deliver power.

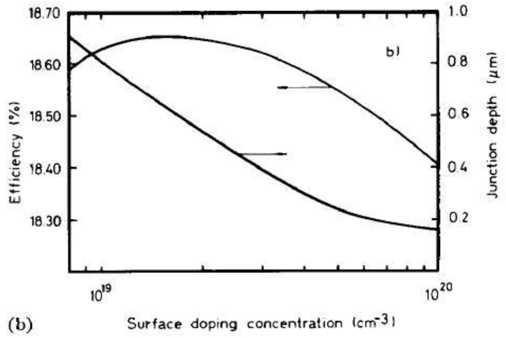


Figure 9: effect of junction thickness and doping level on efficiency

Metal semiconductor contacts are of two types,

A) Rectifying contacts (Schotty contacts),
B) Ohmic contacts.

Rectifying contacts for solar cells will not be discussed, though MIS(Metal Insulator Semiconductor) cells are fabricated but their efficiency is low. Major focus will be on the Ohmic contacts. Ohmic contact is the one which is more important for conventional solar cells. These contact is of two types,

1) Simple Ohmic contact,
2) Tunneling contact.

The nature of metal semiconductor contact i.e ohmic or rectifying depends on the work function of the metal and the electron affinity A of the semiconductor. A barrier is formed in both the cases and external electric field affects the barrier height this is the case for rectifying contacts. In the case of ohmic contacts the barrier present does-not have any hindrance to the flow of carriers in both the directions. For a ohmic contact Fig.10 between metal and n+ type semiconductor the of the metal has to be less than the electron affinity of the n+ material. Were as for p type material it is other way round. Φ of metal has to be more than electron affinity of p+ material. If these convention is not followed then it results in a rectifying contact. Another way of achieving the ohmic contact is by heavily doping the semiconductor region which is below the metal. The heavy doping also helps in generating surface fields which reduces the recombination at the metal semiconductor contact. Heavy doping is called as tunneling in 17 which the barrier height is reduced and the carriers can just tunnel through the junction with out any apposition in either direction from the electric field forming an ohmic contact. Table.1 gives the Work function for various metals and semiconductors, which are used for metallic contacts in Si solar cells. Metals & Semiconductor Work function

Table 1: Work functions

Metals & Semiconductor	Work function Volts
Al	4.3
Cu	4.45
Ag	4.35
Au	4.85
Ti	3.9
Ni	4.5
Cr	4.52
Si(n^+)	4

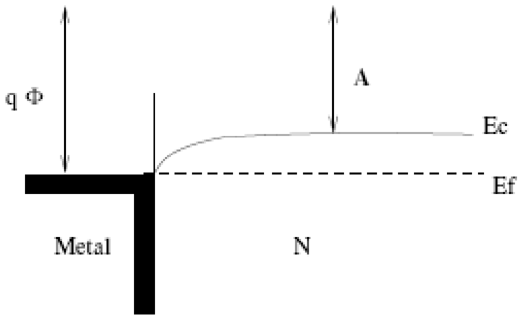


Figure 10: Ohmic Contact

The resistance of the metal semiconductor contact is measured with respect to specific contact resistance Rc (Ω-cm^2). Typically it is of the order of 10^{-5}cm$^{2.}$ Rc is a function of barrier height qΦBn in low doped semiconductor,

$$R_c \alpha \exp^{q\phi B_m / kT} \qquad (14)$$

for heavily doped semiconductor(tunneling) Rc is the function of $(N_d)^{1/2}$ the doping density,

$$R_c \alpha \exp^{\alpha\phi B_m / \sqrt{N_d}} \qquad (15)$$

In low doped metal semiconductor contact the specific resistance is a strong function of barrier height ΦBn were as in heavy doped metal semiconductor contact the Rc is a function of doping density and decreases with increase in doping density. To decrease the contact resistance (not specific contact resistance) the area of the metal to semiconductor contact needs to be increased so that current collection increases. When solar cells operate at high concentrations the Rc is suppose to be very low as high value would cause higher power loss and decrease efficiency as shown in Fig.11. Solar cells have metallic contact at both the places top as well as bottom. The top contact is in the form of grids and bus bars were as the bottom contact is in the form of the metallic plate which covers entire back area of the solar cells. The metal semiconductor contact resistance depends on the area of the contact. Higher the area lower is the contact resistance and vice versa. Fingers in the front contact are about 50m the number of grid lines on the front surface could be increased if 30m or less size of grid lines are fabricated. Thiner size of grid line will accommodate more grid lines in the front surface, this would improve current collection and reduce the metal semiconductor contact resistance. Also the contact resistance depends on the number of grid lines n and the relation is given as R_{ct} = n so as n inscreases the resistance decreases. This is due to reduction in current crowding at the periphery of the contact

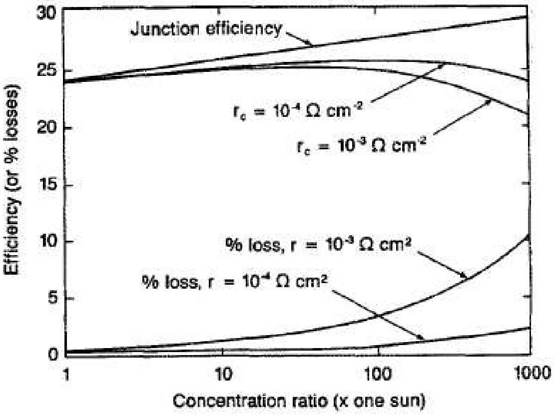


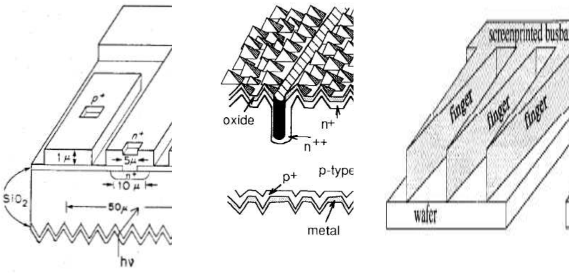
Figure 11: effect of concentration ratio and R_C on efficiency and loss in solar-cells

4.3 Metal fingers and Bus bars

Metal fingers and bus bar resistance causes considerable loss of power in the solar cells. Metal contacts are placed on the front surface and back surface of the solar cells to collect carriers and pass them to the load. Front contact metal is in the form of fine grid lines were as the back contact is a metal plate covering entire back surface. Metals used for the contact resistance are Al; Ti; Pd; Ag ,etc. Back contact metal is Al were as for front contact the finer grid lines are of high conductivity metal usually Ag or paste of Ag; Pd or Ti is used. These contacts are deposited on semiconductor by using various techniques such as Photo-lithograpy, Evaporation, Sputtering, CVD, Screen printing, Electroplating. Conventional solar cells use screen printed contacts with Ag; Al paste. For finer grid structures of about 30 m photolithography is used but this technique is very expensive and is not suitable for the solar cells. Solar cells operating at high concentration have considerable power loss in the metal grid as the losses are proportional to X2 where X is the geometrical concentration ratio as discussed earlier. Reducing resistance is one of the major challenge in such cells. Solar cells having screen printed contacts cannot be used for concentrator solar cell due to lower metal density which results in increase resistance. To reduce the resistance of contacts, an electroplating of high conductivity metal (Ag) on screen printed contacts is a good option. Electroplating has good metal density which causes decreases in the resistance and can improve the performance of solar cells at high concentration ratio. Shading is caused due to the fingers and bus bars on the top surface. This reduces the carrier collection. To avoid shading various other techniques are employed such as inter-digitated back contact in which the both the contacts are placed at the back surface and entire front surface is exposed to light. Another approach is the metal contact solar cell which has front metallic contacts metal in the emitter layer. This improves the aspect ratio(height/width) and reduces the metal resistance. Conventional screen printed contacts cells having H grid structure are modified by using different fingers design to avoid shadow loss and also to reduce the metal resistance. It is clear from the discussion that the series resistance of the solar cell causes power loss and decrease the efficiency of the cell. The possible measures that can help to reduce the series resistance are as follows,

1. High conductivity base (substrate) material oat zone(Fz) , zochralski(Cz).
2. Optimizing the the junction depth for reducing the emitter resistance. Increasing the thickness to reduce the sheet resistance.
3. Increasing the number of fingers by reducing the width increases the current

collection and reduces the metal semiconductor contact resistance.



(a) (b) (c)

Figure 12: a). Interdigitated Back contact solar cel
b). Burried contact solar cell
c). H grid design solar cells

4. Electroplated metal contacts to reduce the resistance of the metal contacts by increasing the metal density.

5. Different etallization techniques Burried contact, H design, Back contact.

6. Use of different techniques for depositing metal contacts at the front and back surface. This is called as the Hybrid contacts. This can reduce the cost of deposition of metals.

5 Thermal Losses

A major portion of loss in solar cell is a due to heat. Light absorbed by the solar cells has excess energy than that required for generation of electron hole pair (band-gap energy Eg). This excess energy is released in the form heat Fig.13. This thermal energy causes rise of temperature of cell. The parameters that are affected by the temperature of the cell are band gap energy, diffusion length, minority carrier lifetime, intrinsic carrier density. The increases in diffusion length and minority carrier concentration and intrinsic carrier concentration and decrease in band gap energy causes the increases in the reverse saturation current Io Eq.16. The increase in Io reduces the open circuit voltage Eq.17 which degrades the efficiency of the cell.

$$I_o = \frac{qD_n n_i^2}{L_n N_A} + \frac{qD_p n_i^2}{L_p N_D} \qquad (16)$$

$$V_{OC} = \frac{kT}{q} \ln \frac{I_{SC}}{I_O} \qquad (17)$$

Temperature effect is more pronounced in concentrator cells. Depending on the concentration ratio, temperature of the solar cell can rise above 1000C. At such a high temperature the solar cell efficiency decreases due to reduced Voc. If temperature rise is kept within limits with the help of proper cooling arrangements, with use of heat sinks or heat pipes, thermal losses could be maintained within limits.

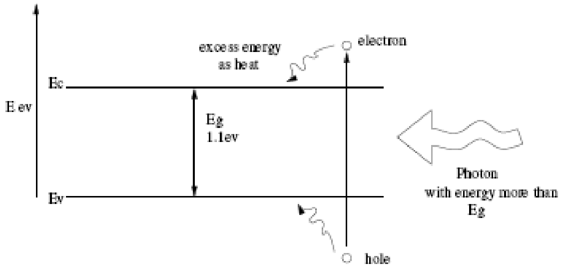


Figure 13: Thermal Loss

6 Efficiency Dependence on Losses

The efficiency of the solar cells is given in terms of the Isc(short circuit current), Voc(open circuit voltage) and the F:F (fll factor) of the solar cells.

$$\eta = \frac{V_{OC} \times I_{SC} \times F.F}{P_{in}} \qquad (18)$$

Eq.18 shows that efficiency depends on Isc, Voc and F:F . These factors are solar cell parameter and every solar cell performance is measured with the help of these parameters. These parameters also indicate the losses prevailing in the solar cells as discussed. A table of losses and the parameters which

Table 2: Losses affecting the parameter

Loss mechanism	**Parameters affected**
Reflective loss	Ioc
Recombination	I_{oc},V_{oc}
Series Resistance	F.F
Thermal loss	F.F,V_{oc}

it affects can be tabulated and is shown in Table.2 From Table.2 we can observe that any decrease in the loss will result in improving the efficiency of the solar cells. Losses and the solar cell parameters are closely linked with the performance of the cell. Fig.14 shows the losses occurring in the solar cell due to various mechanisms discussed in the report.

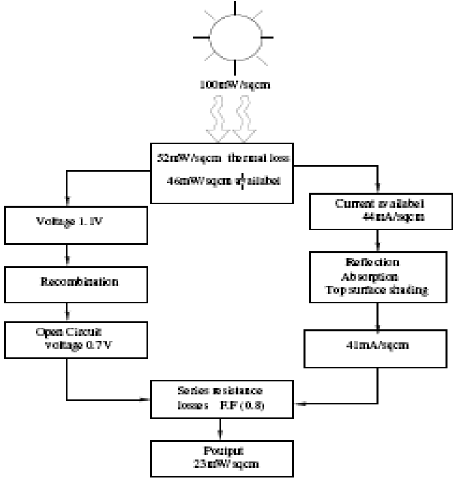


Figure 14: Losses in solar Cell

7 Conclusion

Various mechanism of losses occurring in the Si solar cells are briefly discussed. Recombination, Reflective, Resistive, Thermal are the major losses occurring in the solar cells at 1 sun solar concentration. At higher concentration levels the resistive losses become dominant. Various schemes for reduction of losses such as Surface passivation using Si_3N_4, SiO_2 for reduction in SRV at the front and back contacts, ARC for reducing the front surface reflection and increase the absorption of photons, Different metallization techniques like Electroplated contacts, Burried contacts, H grid design for reducing the metal resistance, Optimum thickness of emitter layer to reduce the sheet resistance of the emitter layer and thus reducing the series resistance, Heat sinks for removing excess heat from the solar cell. Are some of the methods commonly applied over the years by researchers to reduce losses and improve efficiency. Solar cells parameters i.e Isc, Voc, F.F are dependent on losses also these parameters decide the efficiency of the solar cell. A table consisting of Type of loss and the parameter which it affects is tabulated.

Acknowledgement

It gives us a great sense of pleasure to produce thisResearch paper in “Losses in Solar Cells” We owe special depth of Dr. K.A Mishra, Dr. S.K. Mishra, Mr. J.K. Dwivedi , Mr. C.N. Singh , Mr. Jameel Ahmad , Mr. Sanjeev Saxena and all the faculty members of Department of Electrical engineering HBTI, Kanpur, U.P, INDIA for their full support and assistance during the development of this paper.

References

1. A.R.Burgers. How to design optimal metallization patterns for solar cells. Progress in Photovoltaics:Research and Application
2. Martin Green. High Efficiency Silicon Solar Cells. Trans Tech Publications,1987.
3. J.Coello, M.Castro, I., and M.A.Vazquez. Conversion of commercial si solar cells to keep their efficient performance. Progress in Photovoltaics Research and Applications, 2004.
4. J.Zhao. Recent advances of high efficiency single crystalline silicon solar cells in processing technologies and substrate materials. Solar Energy Materials and Solar cells,2004.
5. L.K.Mak, C.M.Rogers, and D.C.Northrop. Specific conact resistnce measurement on semiconductors. Journal of Physics, Instrumentation,1989.
6. M.A.Green, A.W.Blakers, J.Shi, E.Keller, and S.R.Wenham. High efficiency silicon solar cells. IEEE Transcations on Electron Devices, 1984.
7. Tomas Markvart. Solar Electricity. John Wiley and Sons, 1994.
8. Hans Joachim Moller. Semiconductor for Solar cells. Artech House, Boston,1993.

9. Martin Green. Solar Cells. Prentice Hall., Englewood Clis, N.J, 1982.
10. J.Y.Lee and S.W.Glunz. Investigation of various surface passivation schemes for silicon solar cells. Solar Energy Materials and Solar cells, 2006.
11. L.L.Kazmerski. Solar photovoltaic r& d at the tipping point:a 2005 technology overview. Journal of Electron Spectroscopy and Related Phenomena,2006.