Analysis of Schemes to Improve Efficiency of Solar Cells

Shakil Ahmed, Muhammad Khalid, Muhammad Imran Aslam and Haroon Rasheed

Abstract— **Due to the presence of different losses, the highest efficiency obtained using solar cells is less than 30%, which is quite low as compare to other conventional energy resources. Variety of schemes has been proposed in the literature to improve overall efficiency of a solar cell. This paper presents a review of different schemes proposed for enhancing solar cell efficiency. In this work, we analyze the effect of introducing transparent conducting oxide layer, front and rear texturing, back surface field, multi-junctions, top service passivation, selective ohmic contact, quantum dots, and antireflection coating on the performance of solar cells. We also review major factors that limit the conversion efficiency in solar cells and their remedies which could be incorporated with various schemes to enhance efficiency of solar cells.**

Index Terms—Quantum dots; Transparent Conducting Oxides; Texturing; Back surface field; Ohmic contact; Solar Cells

I. INTRODUCTION

With the advent of industrial revolution, energy needs are growing day-by-day. Moreover, fossil fuel produces smoke, dust and harmful gases, which cause tremendous increase in environment pollution. For this reason, the renewable energy sources such as solar cells, are gaining much research attraction. Solar cell produces power which is nonpolluting and inexhaustible, but at the same time considered an expansive solution to the prevailing power crisis. Therefore, reducing the material and the investment cost of the photovoltaic (PV) cell are the major industrial concerns for further marketing, growth and development of PV power generation. Thedevelopment of thin film solar cell promises reduction in material and cost [1].

For getting enhanced conversion efficiency improved optical and electrical designs are needed. The incident light is not fully absorbed in thin film solar cell due to very small length of the cell.

Hence effective light trapping schemes are significantly important for increasing the conversion efficiency of thin film solar cell. A possible solution is by using transparent conducting oxide (TCO) layer that works as a front electrode as well as part of the back side reflector. TCO layer offers low optical and electrical losses and increases the path length of solar radiation. In addition to this applying texturing on front and rear surfaces and using Anti reflection coating reduces the reflection losses and allow absorption enhancement. The absorption efficiency is further reduced due to thermal and recombination losses which result in lesser number of electron emissions corresponding to the number of incident photons.

Shakil Ahmadk, PAF Karachi Institute of Economics and Technology, Karachi, Pakistan. Muhammad Khalid and Haroon Rasheed, Bahria University, Karachi Campus, Karachi Pakistan. M. Khalid is also associated with PAF Karachi Institute of Economics and Technology, Karachi, Pakistan. Muhammad Imran Aslam, Department of Electronic Engineering, NED University of Engineering and Technology, Karachi, Pakistan. Email: muhammad.khalid@bimcs.edu.pk

In this paper we present a review of various techniques that are proposed to enhance efficiency of solar cells. The paper is organized as follows. Section II reviews effect of thermal losses on the efficiency of the solar cell and possible solutions to decrease these losses. Section III provides an account of recombination losses and it remedies. Section IV provides the details of effect of reflection losses on to the efficiency of solar cells and how these may be improved. In section V, we review the effect of series resistance losses and possible approaches to minimize these losses. Section VI concludes the paper.

II. SCHEMES FOR REDUCING THERMAL LOSSES

In a traditional solar cell, much of incident solar energy is not translated into electrical energy. Solar cell irradiance has photons with energies from about 0.5 to 3.5 eV. [2]. Photons with energy lower than the band gap of cell material is just transmitted through the cell without absorbing as they have not enough energy to expel an electron from valence band to conduction band while those with energies higher than band gap E_g generate electrons and holes with an excess kinetic energy equal to the difference between the photon energy and band gap energy. These carriers with excess kinetic energy called hot electrons and holes relaxed to valence band and conduction band releasing energy in the form of heat to the lattice vibration called phonon emission. This is the major limiting factor in the conversion efficiency in single junction cell. The open circuit voltage of a solar cell is given by

$$V_{oc} = \frac{kT}{q} \ln \frac{I_{sc}}{I_o} \quad (1)$$

Where, I_{sc} is short circuit current, I_0 is reverse saturation current, T is temperature in kelvin, K is Boltzmann constant, q is charge of electron. The increase in cell temperature causes the increase in reverse saturation current and decreasing the open circuit voltage of cell and overall efficiency (η) of the cell given by

$$\eta = \frac{V_{oc} \times I_{sc} \times F.F}{P_{in}} \quad (2)$$

Where $F.F$ is the fill-factor of the solar cell and P_{in} is the incident solar power. Variety of schemes has been reported to reduce thermal losses as discussed in subsequent subsections.

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A. Multijunction solar cells

One scheme to reduce this loss and to make better use of solar spectrum is to build multiple semiconductor p-n junction layers with different band gap energies. In this way higher energy photons are absorbed in higher band gap materials and lower energy photons in lower band gap semiconductors. Most common type of Multi-junction cell is triple junction solar cell as shown in fig1. Multi-junction cell absorbs the solar spectrum efficiently thus reducing thermal losses [2].

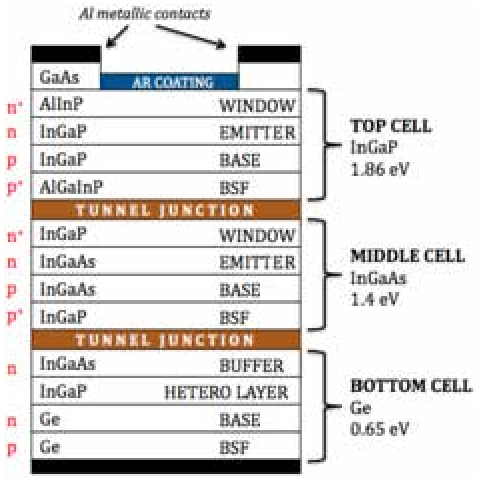

Fig. 1: Tripple junction solar cell structure.

B. Quantum dots solar cells

Another scheme is to reduce thermal losses is to build quantum dots in cell structure. There are two possible approaches to reduce the loss due to absorption of photon energy greater than band gap energy.

One approach is to collect out hot carriers before they cool to enhance photo-voltage and other is to utilize hot carriers to produce two or more electrons-hole pairs (EHPs) to increase photo currents in solar cell [3]. This is known as multiple excitation generation in quantum dots. This process is known as impact ionization in bulk semiconductor

To cause impact ionization in bulk materials requires very high energy of photons which is several times higher than band gap of materials [4]. It means photons which can cause impact ionization have shorter wave length lie in the ultraviolet region (200nm to 400nm). In conventional solar cells high absorption occurs with photon wavelength from 400nm to 875nm. This effect in bulk materials is rarely observed as energy threshold is very high.

In quantum dots cell three dimensional carrier's confinement and increase in coulomb potential reduces the impact ionization energy. Three dimensional quantum confinement effects produce quantized levels for carrier's energy density states which slow down the scattering impact between phonons and electrons. This results in considerable decrease in the rate of energy relaxation which increases the effect of collision ionization [6].

C. Intermediate bands

Another scheme to utilize the energy of photon less than band gap energy is to introduce intermediate bands in the cell structure improving the solar cell efficiency.Intermediate bands are located between the conduction bandand valence band of semiconductor materials [5]. Photon with less energy than bang gap can contribute photo currents by exciting electrons from valence band to intermediate band and from intermediate band to conduction band as shown in fig. 2. Structure of intermediate band can be formed by an array of quantum dots in cell.

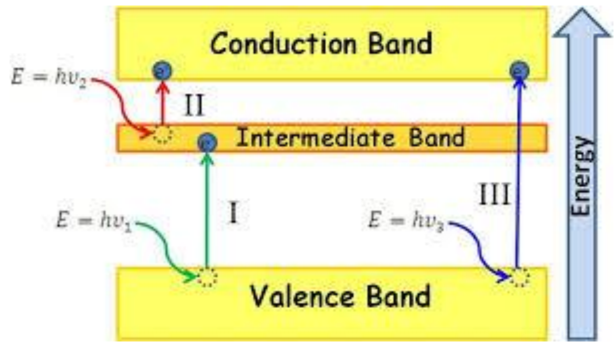

Fig. 2 : Effect of intermediate bands in the transition of electrons from valence band to conduction band

III. Schemes For Reducing Recombination Losses

Solar cells generally consist of different layers namely emitter, depletion and base. Incident light on solar cell material creates EHPs called carriers.These carriers need to be collected by electric field in depletion region before they recombine. Carriers are generated with different rates in different layers of a cell and their recombination rate is also different in different layers .There are different schemes reported to reduce recombination losses are as summarized below.

A. Top surface passivation

Light is incident on cell from top surface of the cell. Top surface is the highest generation region of carriers. There are large numbers of uncovered bonds on the surface called dangling bonds. These bonds are highly reactive and recombination rate of carriers is very high on the top surface. To reduce surface recombination loss top surface is passivated to fill the dangling bonds by thermally grown SiO_2 or SiN layer [7].

In solar cell ohmic metal contact is used to connect the cell current to external circuit. Therefore region around contact cannot be passivated using silicon dioxide insulator. Under the top contact, cell is highly doped to produce barriers for keeping minority carriers away from the contact.

B. Back surface field

Recombination loss also occurs at the rear surface of solar cell.To minimize recombination at the back surface,the back layer is heavily doped as compared to base region to create a Back Surface Field (BSF) barrier for minority

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carrier to keep away from back contact. A typical solar cell band diagram (Fig. 3) shows barrier created by BSF at rear of the cell. The conversion efficiency of solar cell increases with the introduction of BSF [8]. The p-p$^+$ shows a barrier generated by BSF at the back of solar cell.

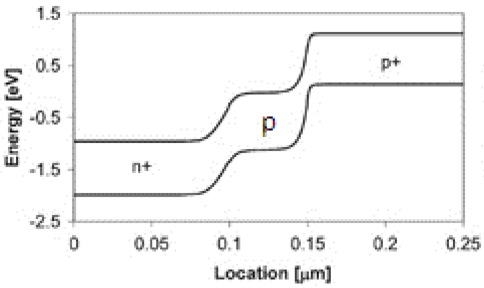

Fig.3: The band diagram of a typical solar cell with BSF.

C. Depletion region recombination loss

Depletion region recombination is less significant as compared to the surface recombination. Any carrier generated in depletion region is readily swept across the device by the strong electric filed present in the region before they recombine.

D. Base/Bulk Material Recombination

In solar cell base region is thick as compare to emitter region. Emitter region is heavily doped as compared to base region and junction electric field is spread more into the base than emitter to collect the generated carriers effectively from base. Dominant recombination mechanism of carriers in this region is due to impurities defects that create energy states in the band gaps acts as trap for carriers. This is known as trap assisted recombination. Shockly and Reed Hall modeled this phenomenon by the equation [9].

$$U_{SHR} = \frac{pn - n_i^2}{\tau_{po}(n + n_1) + \tau_{no}(p + p_1)} \quad (3)$$

Where U_{SHR} is Shockly Reed-hall recombination rate, p and n are respectively the intrinsic carrier concentrations, τ_{no} and τ_{po} are minority carrier life times in *P*- and *N*-regions and p_1, n_1 are equilibrium carrier concentration in *P*- and *N*-regions.

A high purity semiconductor material for base is used to minimize the defects states in band gap of material. A wafer for base is grown by utilizing float zone which has low impurity content.Base is less doped as compared to the emitter to increase the minority carrier diffusion length. Minority carrier diffusion length is the distance traversed by carrier recombination.

IV. SCHEMES FOR REDUCING REFLECTION LOSSES

Light trapping in thin film solar cells is extremely important and enhances conversion efficiency as well as reduces material cost [10].

The reflection loss occurs on the top surface of solar cell, where the entire incident light is not fully absorbed. The absorbed light mainly depends on the absorption coefficient of the material being used and the optical path length. The absorption coefficient cannot be modified since it is a material property. The absorbed carriers are reduced due to reflection and results in reduced short circuit current (I_{SC}). The reflection losses of bare Silicon are more than 30% because the value of silicon refractive index is 3.44. The high refractive index results in absorption of a very small portion of the incident light and for this reason implementation of effective light trapping schemes are crucial for thin film crystalline and microcrystalline silicon solar cells. Generally used light-trapping schemes are summarized in the following subsections.

A. Anti Reflection Coating (ARC)

The reflection losses can be reduced by applying ARC layer on the top surface of a solar cell. ARC is a thin layer of dielectric material with carefully chosen thickness to have interference effects. ARC materials act as an optical impedance matching medium and are used for coupling light efficiently into solar cell structures. Materials used for ARC are SiO_2, Si_3N_4, MgF_2 and ZnS. One of these materials Si_3N_4 gives superior adhesion property with the n-type Si material and hence better surface passivation is obtained. Further reduction in reflection loss can be achieved by using double layer ARC instead of applying single layer coating.

B. Front and Rear Surface texturing

In surface texturing top- and/or rear-surfaces are textured so that reflection is reduced by increasing the possibility of reflected light bounce back onto the surface instead of going out to the surrounding air. This can be achieved in a number of ways. A crystalline substrate is textured by etching along the faces of the crystal planes [11]. If the surface is properly aligned with the internal atoms, the crystalline structure of silicon gives a surface which is made up of random pyramid which is called random pyramid texturing [12]. The inverted pyramid surface texturing is another scheme in which pyramids are etched down into the surface as opposed to etched pointing upwards from the silicon surface [13]. It is reported that the front texturing improves light absorption and external quantum efficiency, whereas the rear texturing enhances these properties only at wavelengths longer than 600nm. The enhancement in short circuit current can be achieved with rear texturing especially in n-i-p solar cells that gives superior result to that of by front texturing [14].

C. Transparent Conductive Oxide (TCO)

A Transparent Conductive Oxide (TCO) is a doped metal oxide thin film used in optoelectronic devices, like flat panel displays and solar cells. TCOs are manufactured with polycrystalline or amorphous microstructures. These applications use electrode materials that have more than 80% transmittance of incident light with conductivities greater than 103 S/cm for efficient carrier transport; with these properties TCO layers work as optically transparent and electrically conductive. TCO also serves additional optical functions like refractive index matching and light scattering. The scattered light is ideally confined within the thin film solar cell and completely absorbed after having multiple passes through the different layers of cell [11]. The front metal contact covers around 10% of the top surface of the cell and causes reflection losses; any light falling on contact surface area will not be absorbed. If the front contact area is made larger its series resistance loss reduces but at

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the same time causes huge reflection loss. Applying TCO layer solves this problem. The TCO layer is used as a contact that collects current without resistance loss and the entire surface is available to collect light. Many materials have been examined as TCO among witch indium tin oxide, zinc oxide and tin oxide are the most prevalent in actual use and offers the best results.

V. Schemes for Reducing Series Resistance Losses

Contributions of Power losses due to series resistance in solar cells are around 20% of the total input power. These losses are combination of emitter layer resistance and Metal Semiconductor (MS) contact (front and back). Emitter region thickness is kept small as compare to the base region thickness so that the entire generated majority carriers can be collected with lesser chances of being recombined with the minority carriers, but having thin thickness of emitter causes increased emitter resistance loss. In the emitter region the direction of current is lateral as shown in the figure.

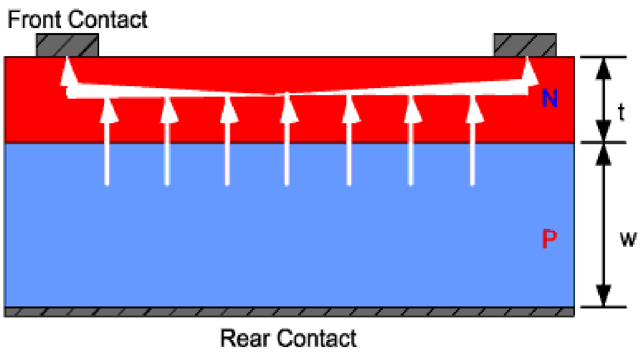

Fig. 4: Current flows laterally towards contacts

This lateral current flow increases path length and hence the emitter resistance. This emitter resistance can be minimized through the optimization of the junction thickness and by achieving suitable doping concentration of emitter region [15]. Another possibility of achieving lower resistance losses is to use TCO as described in section IVB.

The metal to semiconductor contact (MS contact) resistance loss is the other main component of the series resistance loss. MS contacts are of following types:

I. Rectifying Contacts (Schotty Contact)
II. Ohmic Contact
III. Selective Ohmic Contact

Rectifying contacts are usually not used in solar cells where as ohmic contacts are very important. Ohmic contacts can be made between semiconductor and metal by heavily doping the semiconductor material. In ohmic contacts the barrier is present at the MS contact but it does not hinder the flow of carriers from metal to semiconductor or vice versa. The reason is that the width of the barrier is very thin and the carriers can tunnel through the barrier, ideally current flows through the barrier without any voltage drop. Large work function metals are required for making MS contact with p-type semiconductor whereas low workfunction metals are used with n-type semiconductor materials [16]. In addition to this the heavy doping generates surface fields which reduce the recombination at the MS contact. Hence ohmic contacts are used to reduce the losses and improve the efficiency. For better results and further reduction in series resistance losses selective ohmic contacts are used in solar cells. These contacts pass one carrier type only, ideally with no voltage drop. This phenomena is very advantageous in solar cells and facilitates encourage photo carrier separation. The pn junction which acts as a separating engine in solar cells pushes electron in one way and the holes in other way, so having selective ohmic contact recombination reduces and current increases and hence the conversion efficiency enhances.

VI. Conclusion

In this paper, we review different phenomena that reduce the efficiency of a solar cell and possible options to reduce their effects. Losses in the solar cell are divided in to four categories which are (i) thermal losses, (ii) recombination losses, (iii) reflection losses, and (iv) ohmic losses. Thermal losses occur due to dissipation of photon energy in the form of heat due to difference in the photon energy and the band gap energy of the semiconductor used. These losses may be decreased by using multi-junction structure, introducing quantum dots, or creating intermediate bands. Recombination losses occur when the EHPs recombine without contributing to photocurrent. These losses may be reduced by top surface passivation or by back surface field. Reflection losses occurs when the incident light is reflected back in the environment and thus do not contribute to EHP generation. Reflection losses may be reduced by using an antireflection coating at the top surface or by texturing front and/or rear surfaces of solar cell. Another common method to reduce the reflection loss is by using TCO on the top surface. Application of TCO not only reduces the reflection losses but it also helps overcoming the ohmic losses by providing good electrical contacts which occur due to the resistance at metallic-semiconductor contacts.

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